Overview of Polarimetry at RHIC and Elastic $p\uparrow C \rightarrow pC$ Scattering at Very Low Momentum Transfer t

A. Bravar, I. Alekseev, L. Ahrens, M. Bai, G. Bunce, S. Dhawan,
H. Huang, V. Hughes, G. Igo, O. Jinnouchi, K. Kurita, Z. Li,
W.W. MacKay, S. Rescia, T. Roser, N. Saito, H. Spinka, D. Svirida,
D. Underwood, C. Whitten, J. Wood

Dubna – Spin03
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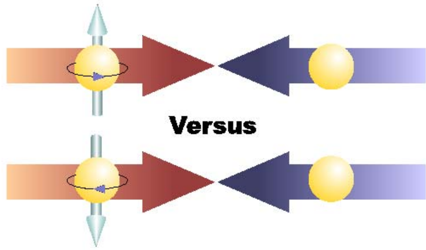
Alessandro Bravar

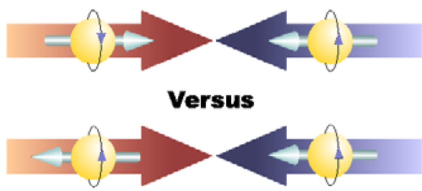
BROOKHAVEN NATIONAL LABORATORY

Polarimetry : Impact on Spin Physics

Single Spin Asymmetries



Double Spin Asymmetries



Physics Asymmetries

$$A_N = \frac{1}{P_B}\left(\frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}\right)$$

$$A_{LL} = \frac{1}{P_B{}^2}\left(\frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}\right)$$

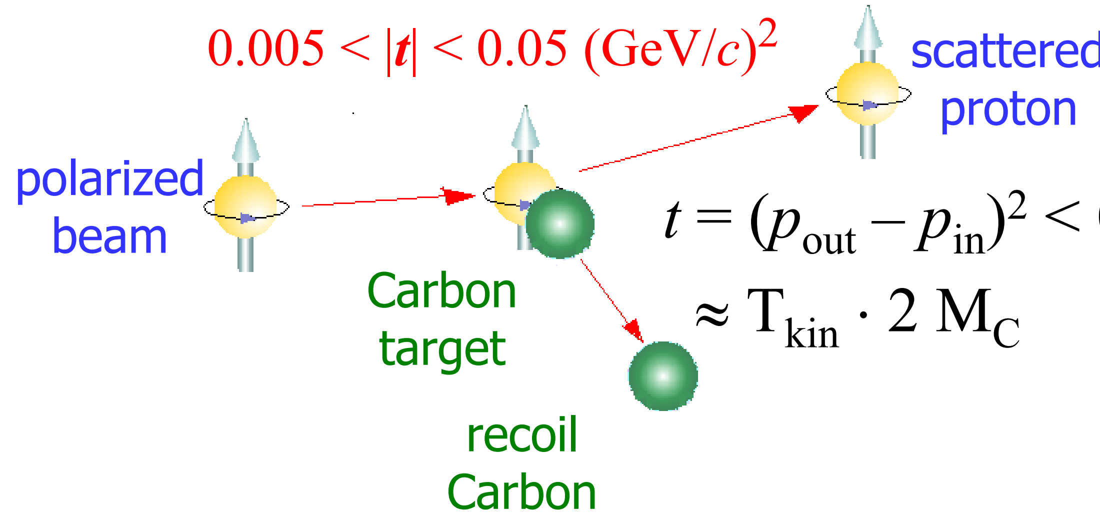
- measured spin asymmetries normalized by P_B to extract Physics Spin Observables
- normalization ⇒ scale uncertainty
- polarimetric process with large σ and known A_N
  - *pC* elastic scattering in CNI region
  - A_N almost calculable, but small ~ 1 – 4 %
  - need absolute “calibration”
- RHIC Spin Program requires $\Delta P_{beam} / P_{beam} < 0.05$

Elastic $pC \to pC$ scattering at low t

$0.005 < |t| < 0.05\ (\mathrm{GeV}/c)^2$

$$A_N = -\frac{1}{P_B} \cdot \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

recoil



$$t = (p_{\mathrm{out}} - p_{\mathrm{in}})^2 < 0$$
$$\approx \mathrm{T}_{\mathrm{kin}} \cdot 2\ \mathrm{M}_{\mathrm{C}}$$

1. $\mathrm{A_N}$ from interference of spin non-flip and spin flip amplitudes
   - $\Rightarrow$ spin dependence of interaction
   - $\Rightarrow$ hadronic spin flip (spin-coupling of Pomeron)

2. Polarimetry
   - almost “calculable”
   - small $\mathrm{A_N} \sim 1\text{–}4\ \%$ $\Rightarrow$ requires large statistics $> 10^7$
   - large cross section
   - weak beam momentum dependence ($\mathrm{p} > 20\ \mathrm{GeV}/c$) ?

A_N: from where does it come?

$$\sigma = |A_{hadronic} + A_{Coulomb}|^2 \qquad (|\mathbb{P} + \gamma|^2)$$

around $t \sim -10^{-3}\ (\mathrm{GeV}/c)^2$ $A_{hadronic} \approx A_{Coulomb} \Rightarrow$ INTERFERENCE

CNI = Coulomb – Nuclear Interference

unpolarized $\Rightarrow$ clearly visible in the cross section $d\sigma/dt$ (charge)

polarized $\Rightarrow$ left – right asymmetry A_N (magnetic moment)

$$A_N = C_1 \Phi_{em}^{flip} \Phi_{had}^{non-flip} + C_2 \Phi_{had}^{non-flip} \Phi_{had}^{flip}$$

$\propto(\mu-1)_p$ $\qquad \propto\sqrt{\sigma^{pp}_{had}}$

QED $\Rightarrow$ "calculable", expect $A_N \neq 0$ up to 4 – 5%

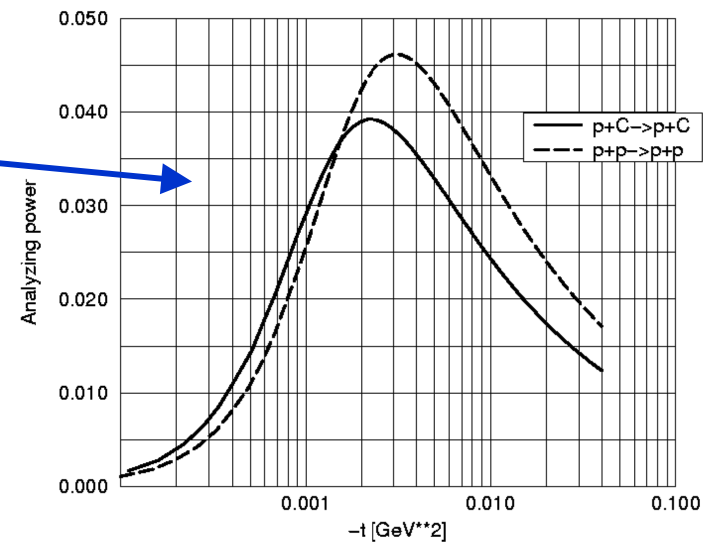
$$A_N = \sqrt{\frac{8\pi Z\alpha}{m_p^2 \sigma_{tot}^{pA}}} \frac{y^{3/2}}{1+y^2}(\mu-1); \qquad y = \frac{\sigma_{tot}^{pA}\, t}{8\pi Z\alpha}$$

QCD $\Rightarrow$ "unpredictable", need direct measurement

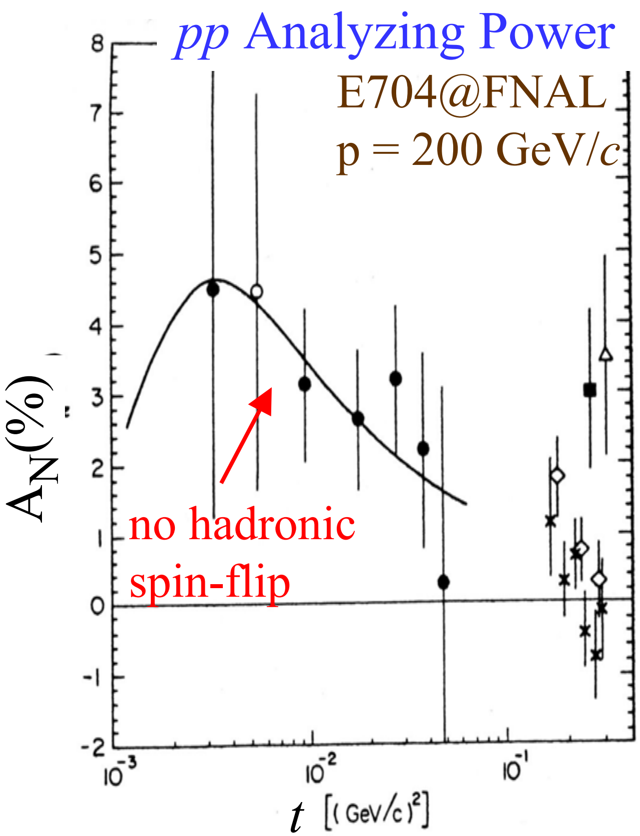
$$g_5(s,t) = \tau(s) \cdot \sqrt{|t|}/m_p \cdot g_0(s,t) \qquad g_0(P,f,\omega,?)$$

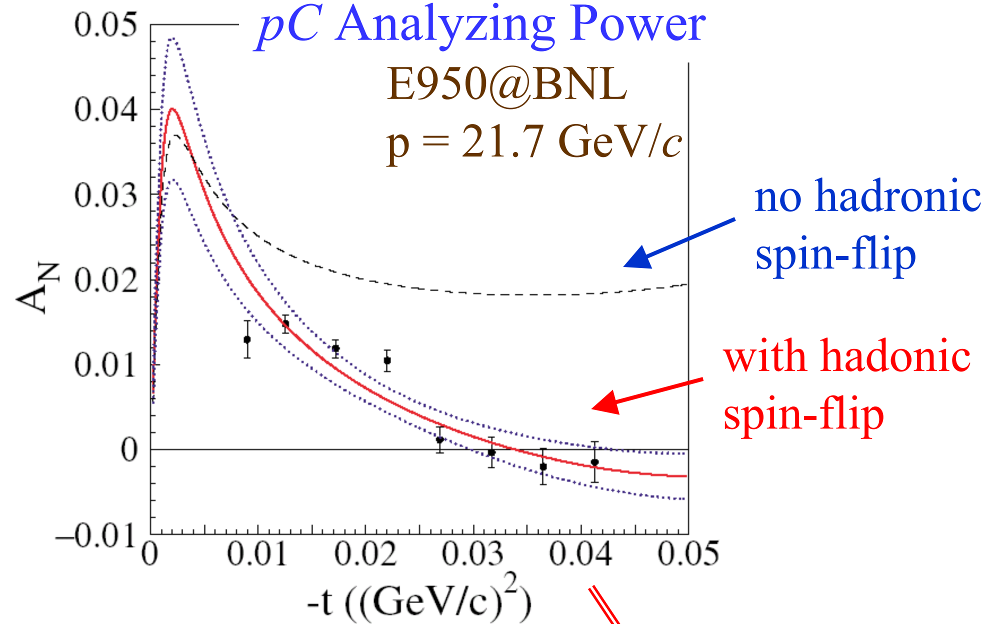
$$r_5^{pC}(s,t) = \tau(s)\big(i + \rho_{pC}(s,t)\big) = m_p/\sqrt{|t|} \cdot F_s^{had} / \Im F_0^{had}$$

B. Kopeliovich & L.Trueman



Some A_N measurements in CNI region





if used for polarimetry

$\Rightarrow \Delta P/P \sim 15 - 20\%$

$$r_5^{pC} \propto F_s^{had} \,/\, Im\, F_0^{had}$$

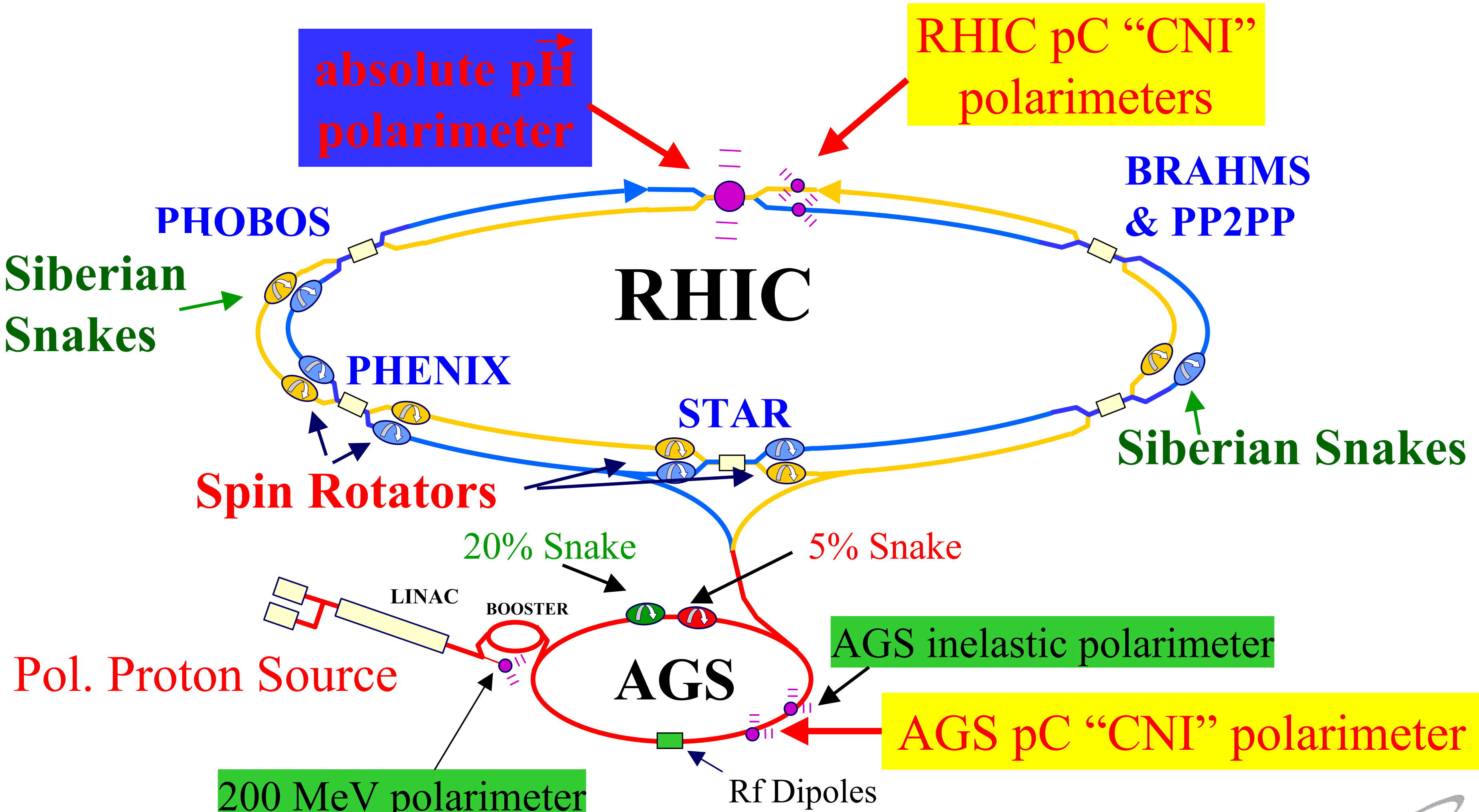
$$\mathrm{Re}\, r_5 = \quad 0.088 \pm 0.058$$

$$\mathrm{Im}\, r_5 = -0.161 \pm 0.226$$

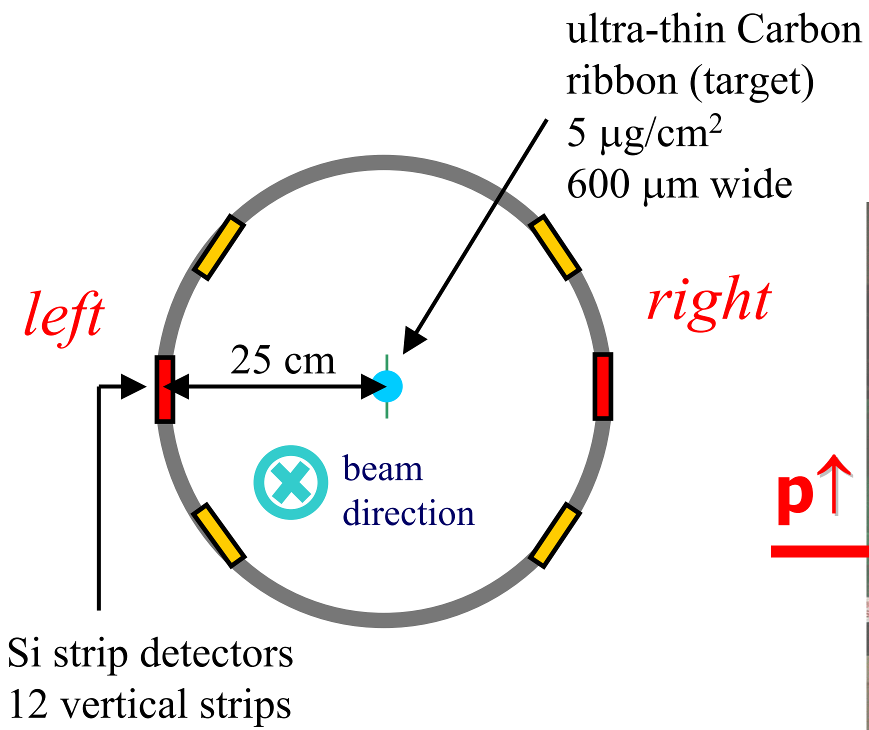
highly anti-correlated

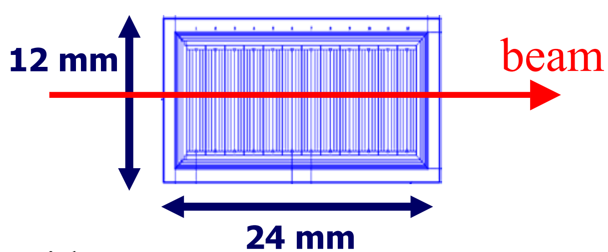
RHIC: the "Polarized" Collider

70% Polarization $L_{max} = 2 \times 10^{32}\ s^{-1}cm^{-2}$ $50 < \sqrt{s} < 500$ GeV

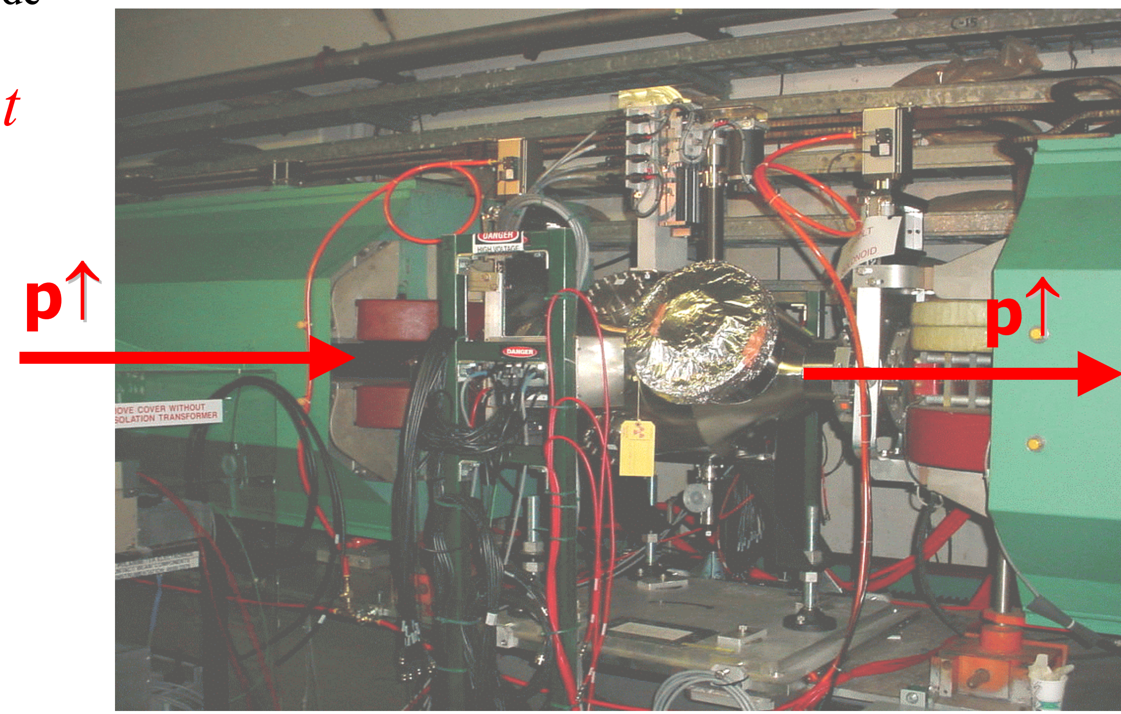


Elastic $p\uparrow C$ Scattering Setup in the AGS Ring





read-out with
waveform digitizers



similar setups in RHIC for each beam

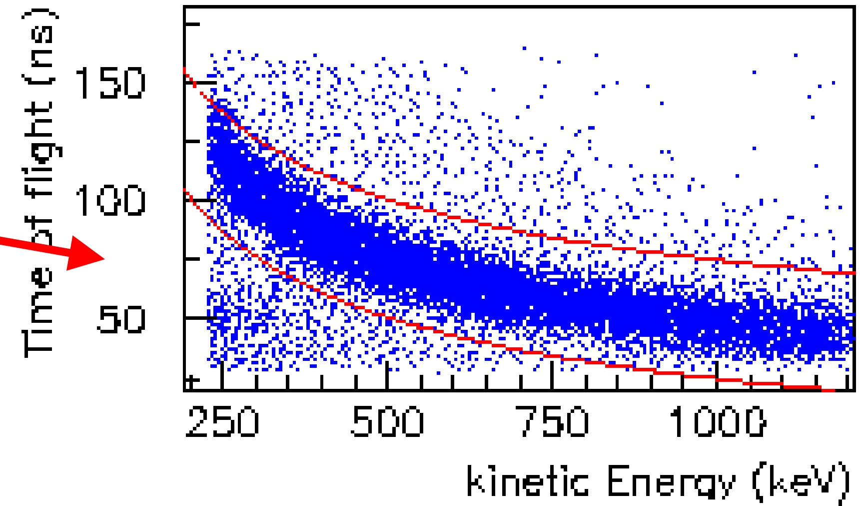
Event Selection

$T_{kin} = \frac{1}{2} M_R \, (dist / ToF)^2$
non-relativistic kinematics

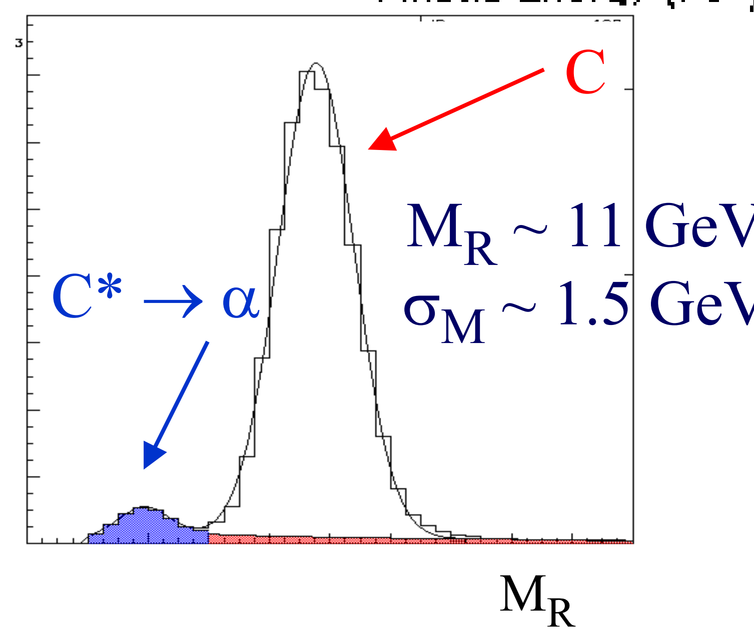
- recoil carbons detected with Si detectors
- "identified" via ToF vs T_{kin} correlation
  $\Rightarrow$ inv. mass recoil
  gives only "particle ID"

  position vs energy correlation spoiled by multiple scattering in target

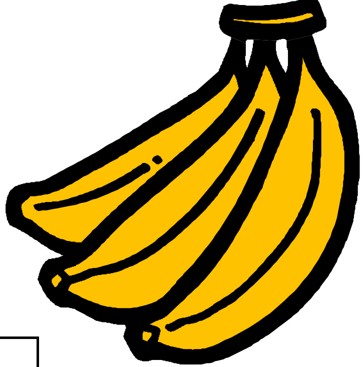
  background from beam dissociation very small for this kinematics



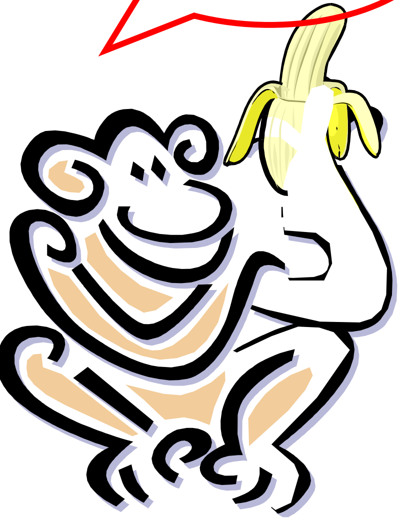
- Δ (Tof) ~ 20 ns from bunch length
  ($\Rightarrow \sigma_M$ ~ 1.5 GeV)
- background events < few %
  within the "banana" cut
- very high event rate (> 10^5 ev/sec/ch)
  events acquired with dead time free wave-form digitizers

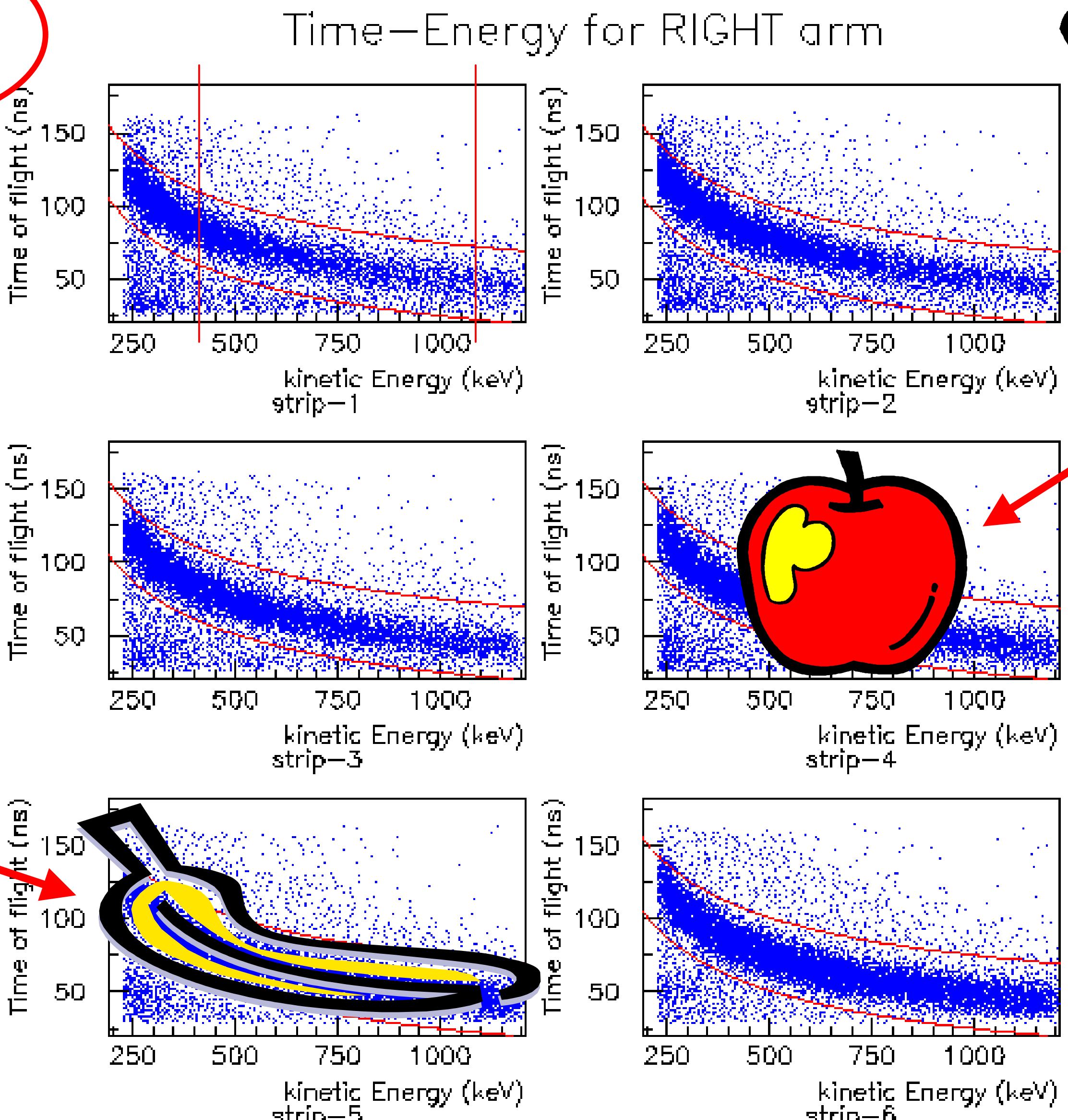


Time of Flight vs. Energy i.e.



event selection

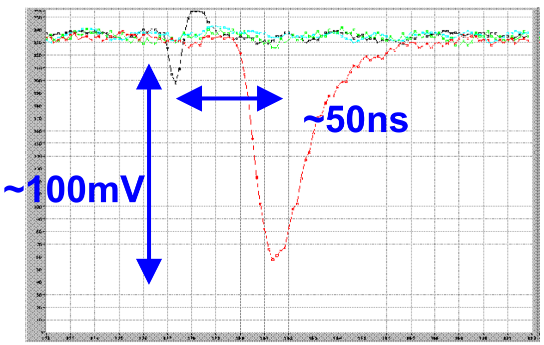




does not pass the cuts

does pass the cuts

DAQ and WFD



ADC
3×140 MHz

synchronized to accelerator clocks
bunch $\times$-ing $\Rightarrow$ “start” TDC

FPGA

“online” analysis of waveform
performed beteween consecutive
bunch $\times$-ing
$\Rightarrow$ PH, tot Q, t.o.f

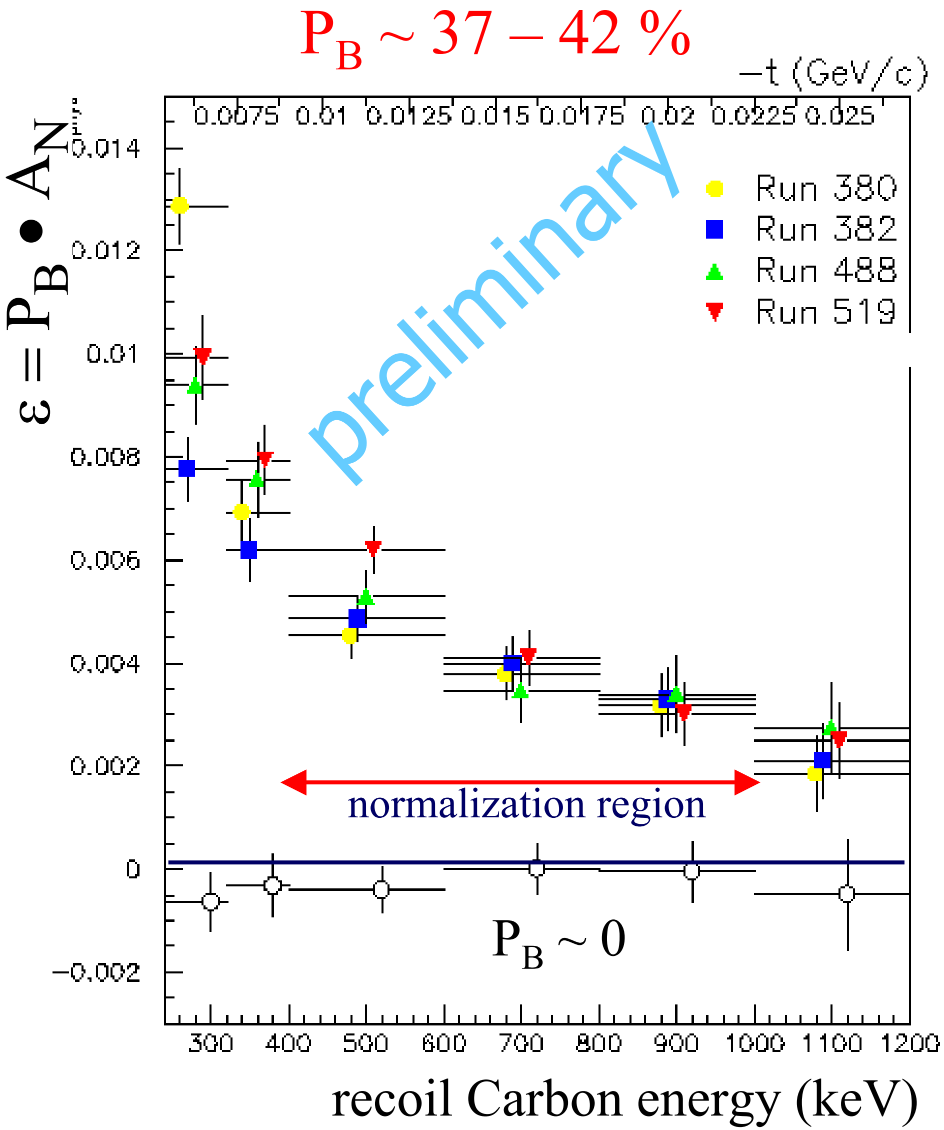
$\Delta t \sim 2$ ns
$\Delta E < 50$ keV

onboard
memory

DAQ PC

Wave Form Digitizer = peak sensing ADC, CFD, …
deadtimless DAQ system $\Rightarrow$ no spin dependent dead time !
can accept, analyze, and store 1 event / each bunch $\times$-ing

$p\uparrow C$ *raw* asymmetry at 24.3 GeV



$$P_{beam} = \frac{1}{\langle A_N \rangle} \cdot \varepsilon_N$$

$$\langle A_N \rangle = \frac{\sum N(t_i) A_N^{th}(t_i)}{\sum N(t_i)}$$

calculated over several ***t*** bins

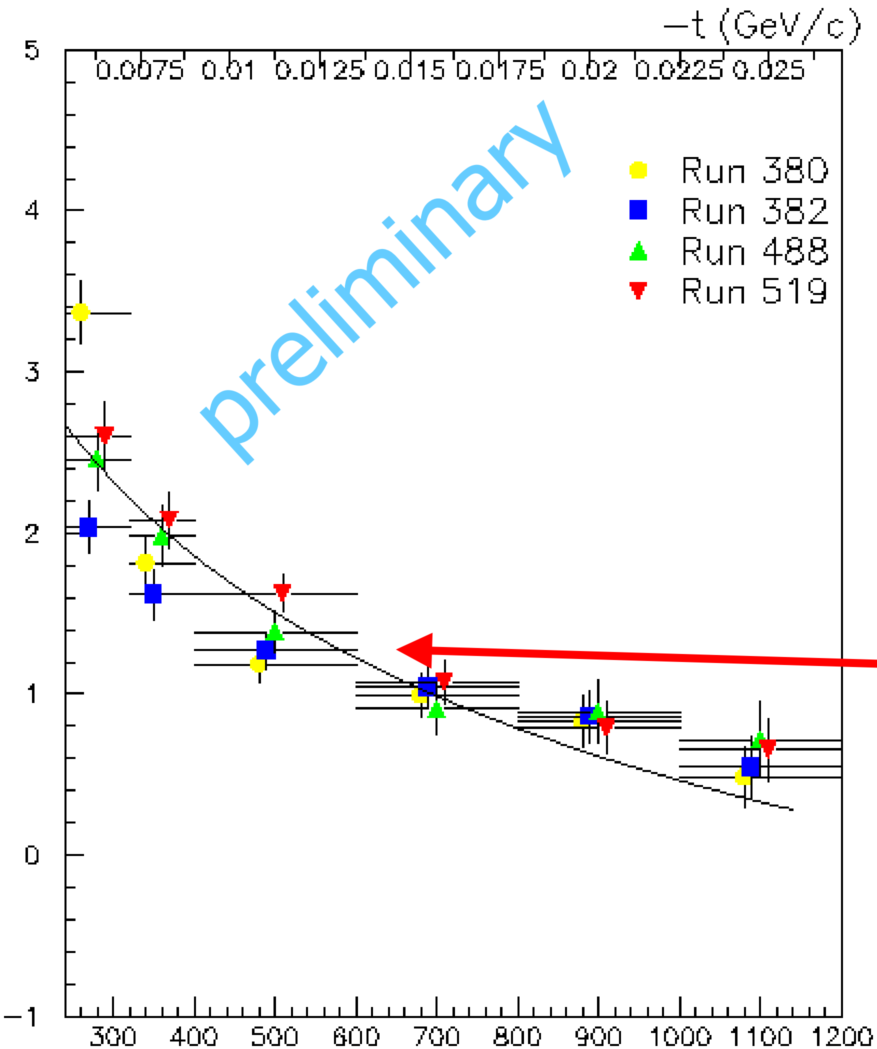
A_N^{th} from a fit to E950 data at 21.7 GeV over similar ***t*** range

L. Trueman hep-ph/0305085

$\langle A_N \rangle \approx 1.12$

$0.009 < |t| < 0.022$ $(\mathrm{GeV}/c)^2$

A_N $p\!\uparrow\!C \rightarrow pC$ at 24.3 GeV



recoil Carbon energy (keV)

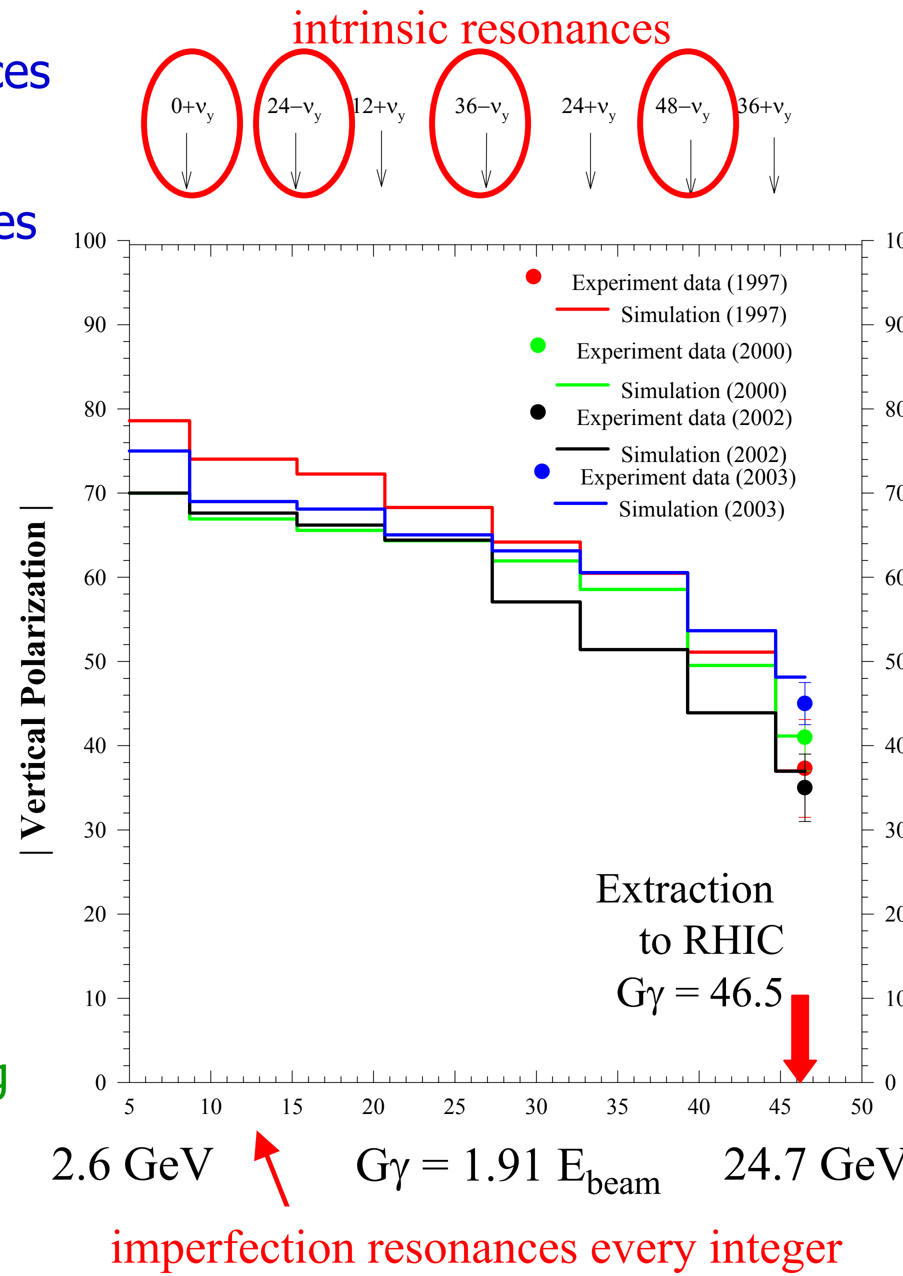
- only statistical errors are shown
- normalization error (i.e. P_B) ~ 25% (relative)
- systematic error (background, pileup, etc.) < 20% (relative)

fit to E950 data
L. Trueman hep-ph/0305085

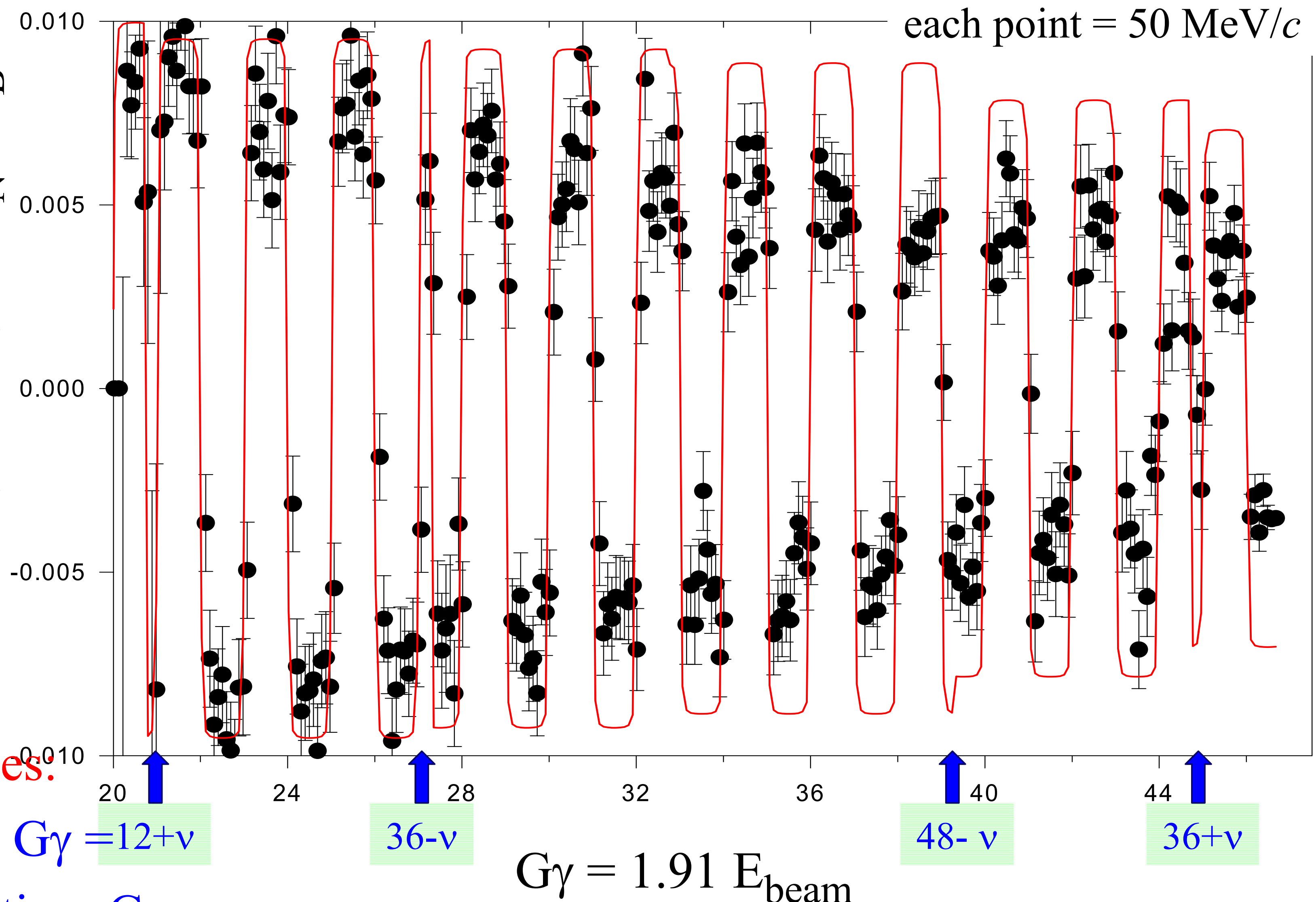
similar behavior E950 ⇒ substantial hadronic spin-flip confirmed

AGS Polarization vs Energy (2003)

- Full spin flip at all imperfection resonances using a solenoidal partial Siberian snake
- Full spin flip at strong intrinsic resonances using an rf AC dipole (spin flipper)
- Remaining polarization losses are from coupling and weak intrinsic resonances
- Almost 2 × improvement (on avarage) compared to 2002 run
- Consistently measured polarizations of 45%; also reached 50% on occasions
- Small emittance beam of 10 π with scraping: intensity ~ 6 x 10^{10} p / bunch
- Add a 5% warm helical snake (run '04)
- To avoid all depolarization build a strong (20%) super-conducting helical Siberian snake snake (2005-2006)



AGS Polarization during acceleration (ramp)



resonances:

intrinsic: $G\gamma = 12+\nu$, $36-\nu$, $48-\nu$, $36+\nu$

imperfection: $G\gamma = n$

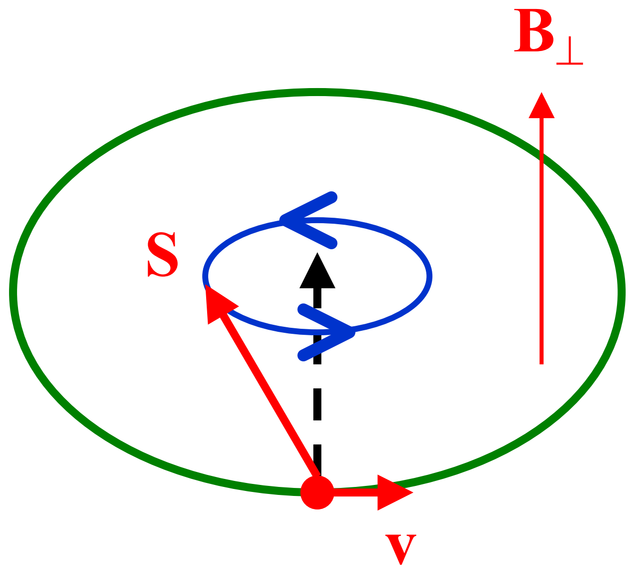
Spin Dynamics

Spin Precession in Laboratory Frame:
(Thomas [1927], Bargmann, Michel, Telegdi [1959])

$$d\mathbf{S}/dt = -(e/\gamma m)\,[(G\gamma+1)\mathbf{B}_{\perp} + (1+G)\,\mathbf{B}_{o}] \times \mathbf{S} \qquad G\gamma = \mathbf{1.91\ E}$$

Lorentz Force

$$d\mathbf{v}/dt = -(e/\gamma m)\,[\quad \mathbf{B}_{\perp} \quad] \times \mathbf{v}$$



- For pure vertical field:
  Spin rotates $G\gamma$ times faster than motion, $\nu_{sp} = G\gamma$

- For spin manipulation:
  at low energy, use longitudinal fields
  at high energy, use transverse fields

Depolarizing Spin Resonances …

Spin tune: Number of 360 degree spin rotations (spin precessions) per turn

Depolarizing resonance condition:
Number of spin rotations per turn = Number of spin kicks per turn

Imperfection resonance (magnet errors and misalignments, closed orbit errors, …):

$$G\gamma = \nu_{sp} = n$$

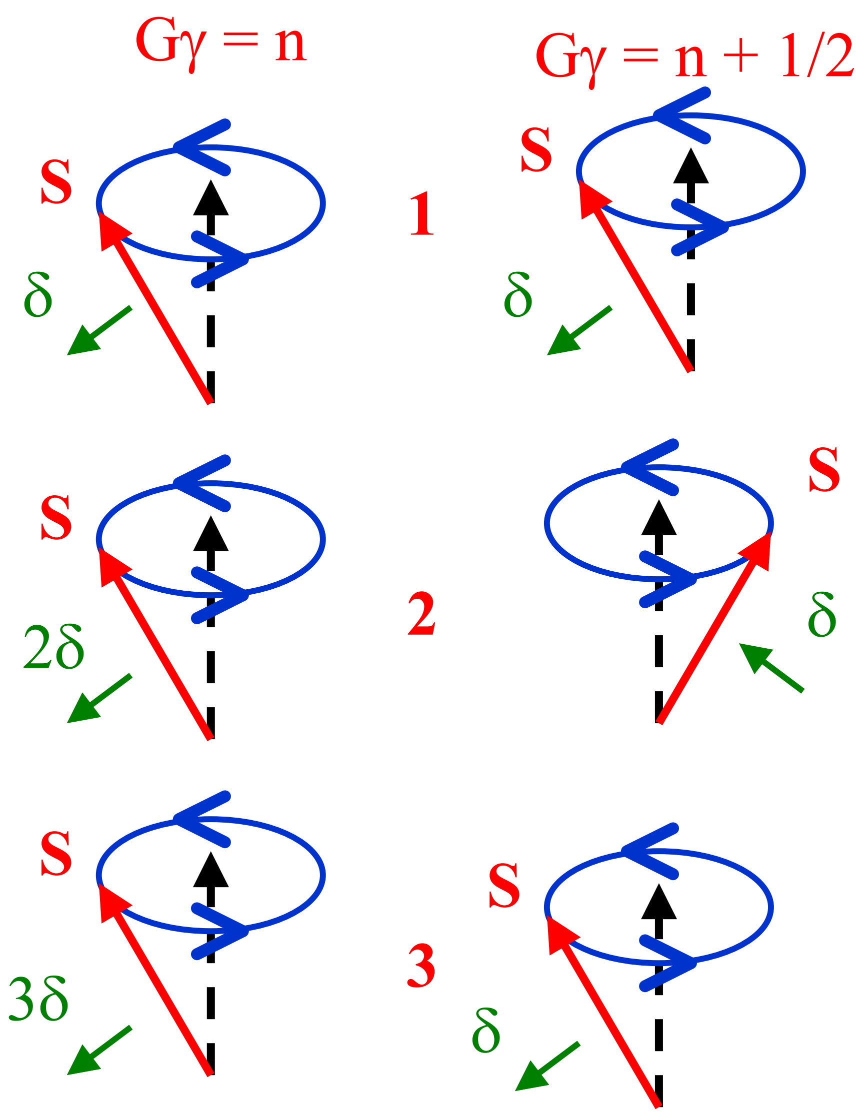
Intrinsic resonance (vertical focusing fields like in quadrupoles, finite beam emittance, …):

$$G\gamma = \nu_{sp} = Pn \pm \nu_y$$

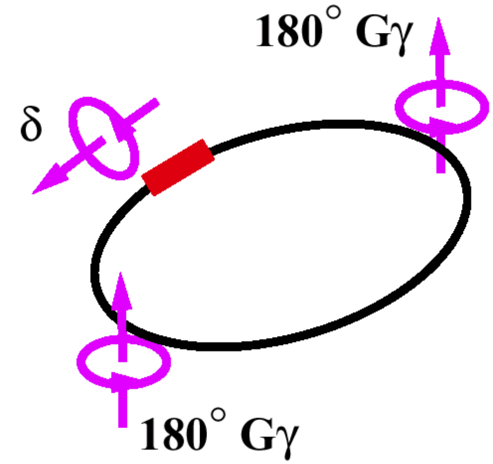
P: Superperiodicity [AGS: 12]
ν_y: Betatron tune [AGS: 8.75]

Resonance conditions can be avoided through the use of "Siberian Snakes" (RHIC) or by forcing a full spin reversal, when crossing these resonances (AGS)

Imperfection Resonances: $G\gamma = n$



partial snake (AGS) = imperfection resoance

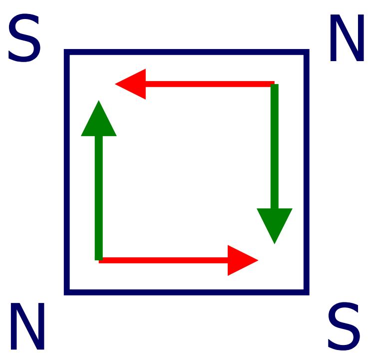


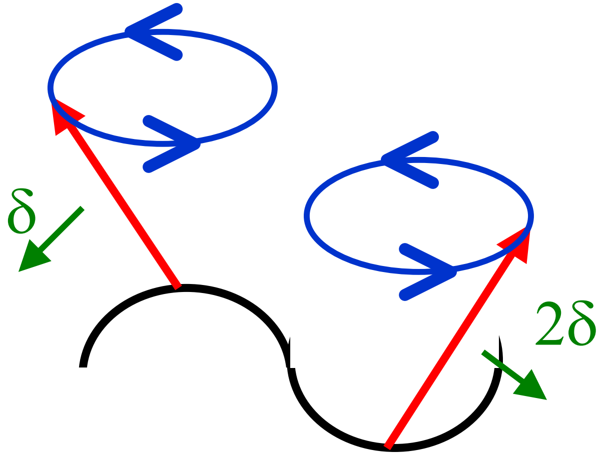
if snake sufficiently strong (5% enough in AGS) spin is fully flipped when crossing an imperfection resonance with no polarization loss

for $G\gamma \neq n$, spin "oscillates" around stable direction, which is tilted from the vertical

Intrinsic Resonances: $G\gamma = nP + \nu$

quadrupole



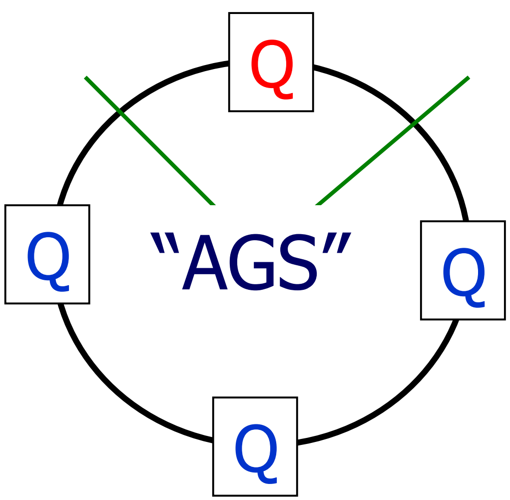


betatron oscillation of frequency ν

if spin precession "in phase" with betatron oscillation $G\gamma = \nu$ when crossing the quadrupole depolarizing kicks δ add

$\Rightarrow$ depolarizing resonance condition

FODO section

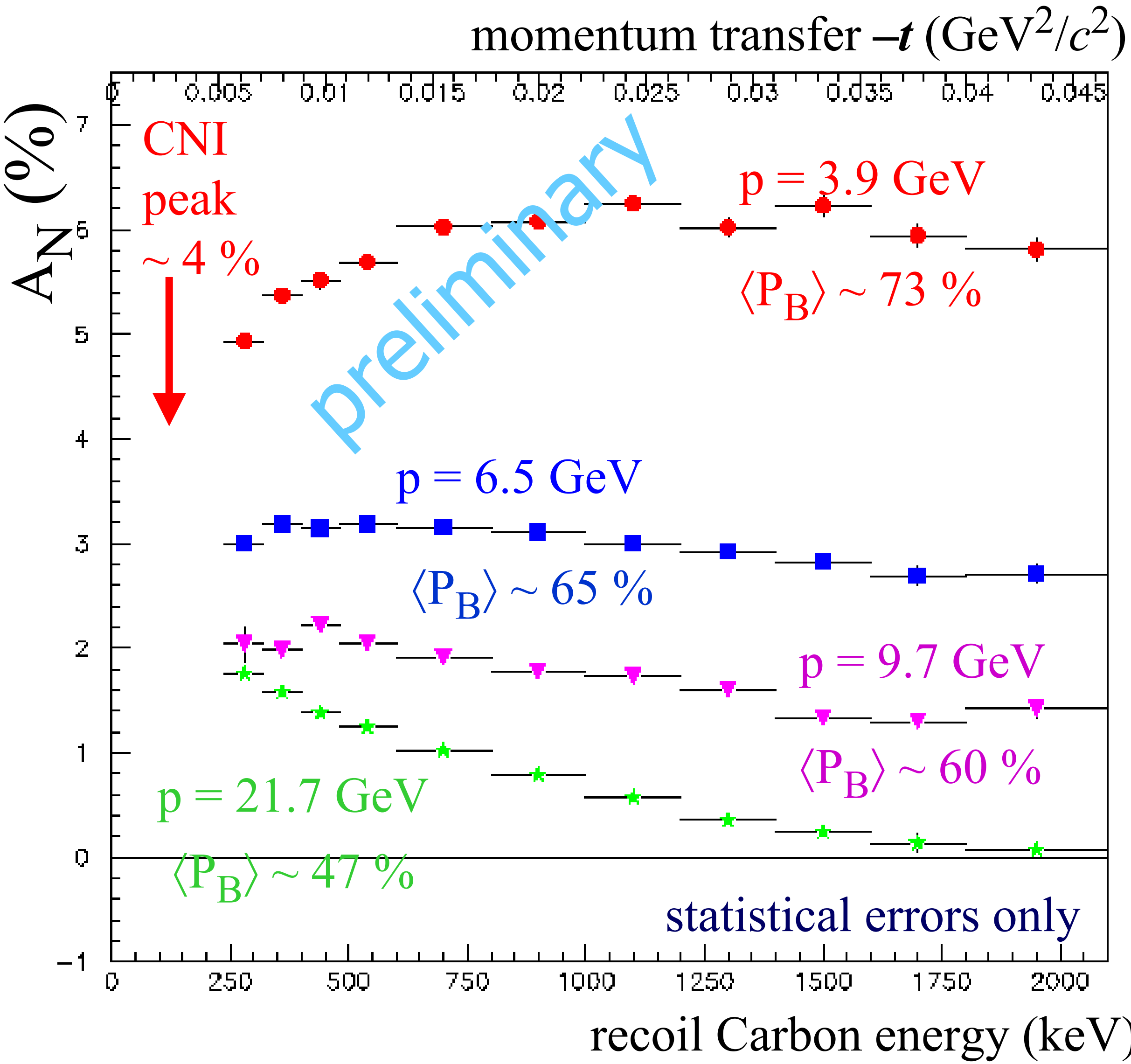


to be in phase with betatron oscillation over a closed orbit spin must precess $n + \nu$ times

in a periodic accelerator spin "in phase" with betatron oscillation when crossing same quadrupole in consecutive FODO section if $G\gamma = nP + \nu$

Polarization losses reduced / avoided by forcing a full spin reversal (flip) using an RF dipole

A_N $p^{\uparrow}C \to pC$ at 3.9, 6.5, 9.7 & 21.7 GeV



only statistical errors are shown

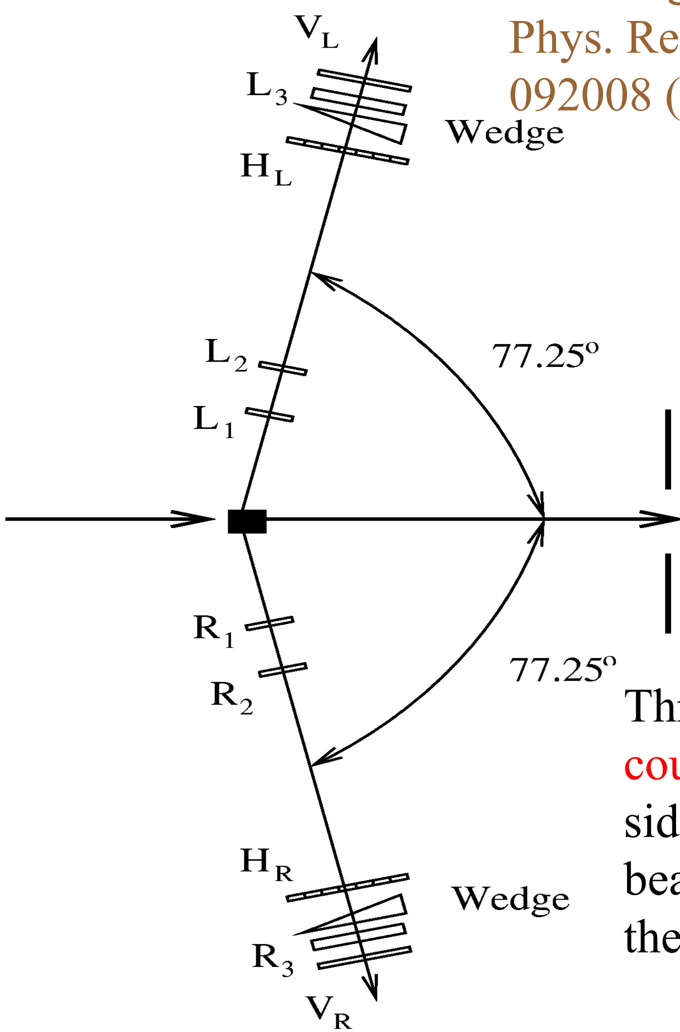
normalization errors:
- ~ 10 % (at 3.9)
- ~ 15 % (at 6.5)
- ~ 20 % (at 21.7)

systematic errors:
- < 20 %
- - backgrounds
- - pileup
- - RF noise

Calibration of AGS pC CNI polarimeter

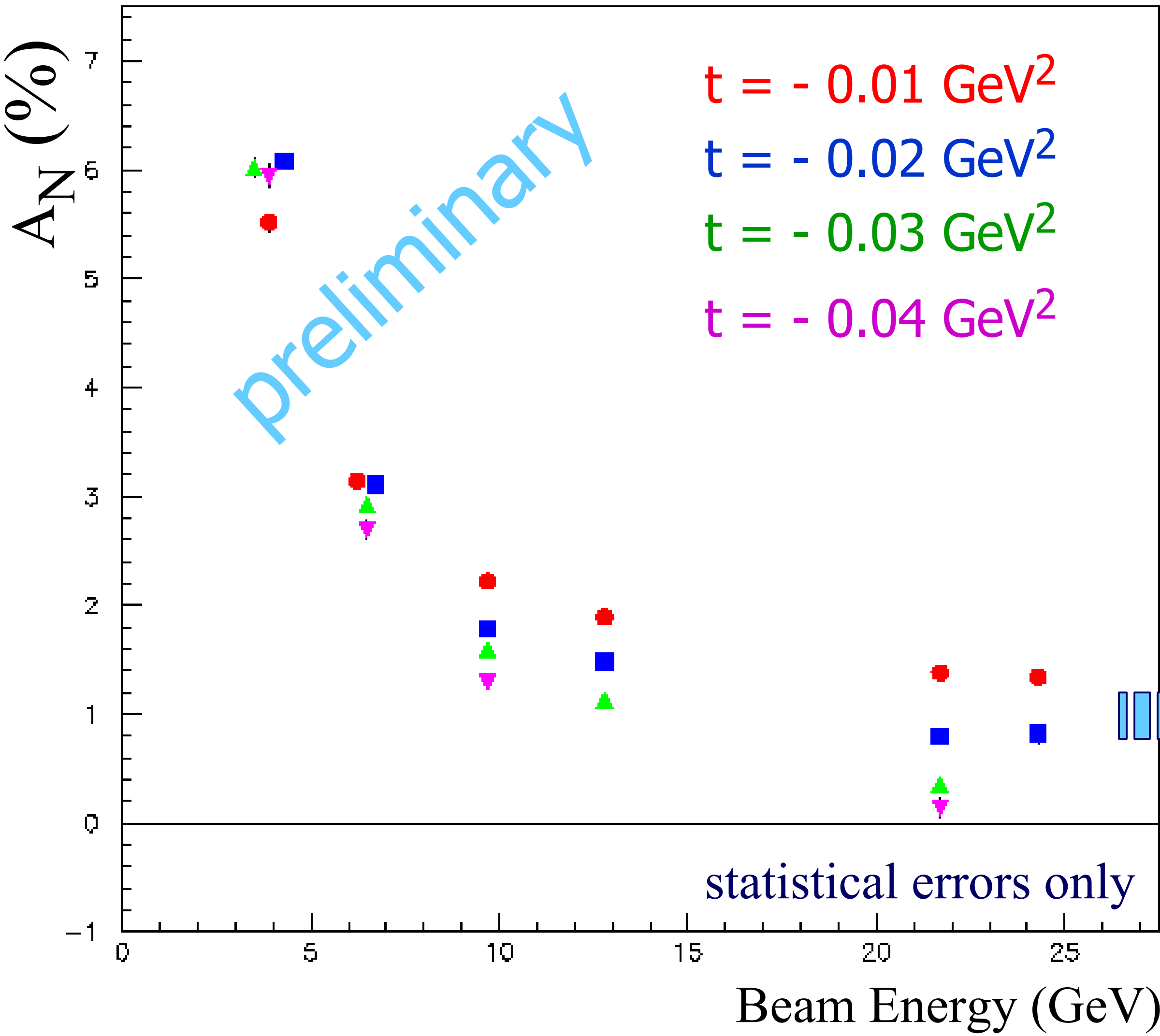
- Quasi-elastic *pp* scattering
  $p\uparrow + C \rightarrow p + p + X$
  at $t \sim -0.15\ \mathrm{GeV}^2/c^2$
- Approximately symmetric recoil telescopes of plastic scintillation counters
- Targets are thin fiber ribbons and nylon (fishline)
- For absolute calibrations forward scintillators were added
  The practical limit to this technique is P < 7 GeV/c (counters outside of beam pipe)
- Use a fit to pp polarization data to find A_N (pp) (NIM 211, 239 (1983))

E880 polarimeter:
C.E. Allgower et al., Phys. Rev. D65, 092008 (2002)



Three forward counters each side of the beam, outside the beam pipe.

A_N $p^{\uparrow}C \rightarrow pC$: Energy Dependence



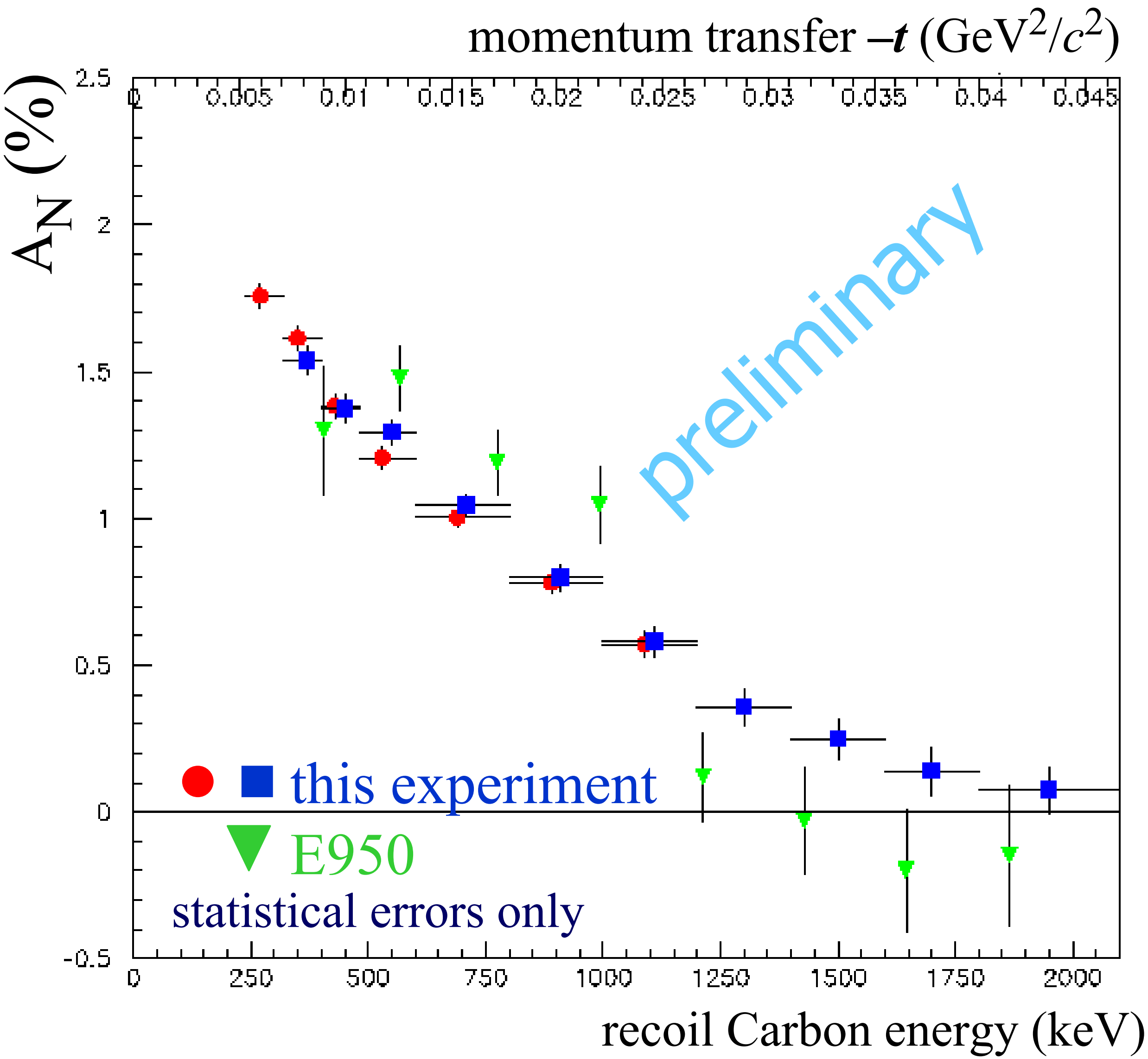
only statistical errors are shown
systematic errors as for previous slide

Asymptotic regime

E ?

No energy dependence

A_N $p\!\uparrow\! C \rightarrow pC$ at 21.7 GeV

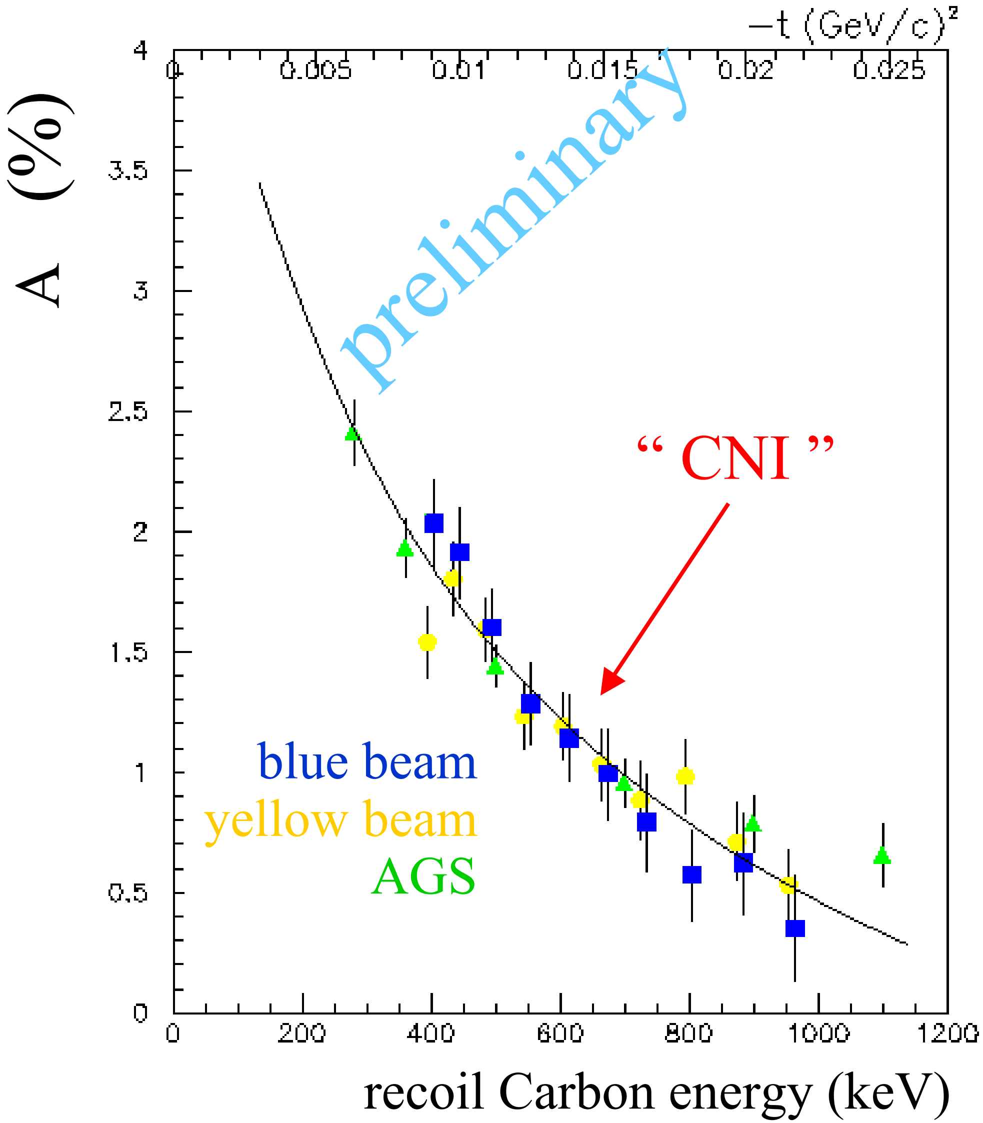


normalized with
$p\!\uparrow + C \rightarrow p + p + X$
quasi-elastic
polarimeter
inside AGS ring
(E880 experiment)
$\Delta P_{beam} / P_{beam} \sim 20\%$

only statistical
errors are shown
(also for E950)

systematic error < 20%

A_N: $p^{\uparrow}C \rightarrow pC$ at RHIC energy (100 GeV)



for normalization assume
A_N (24.3 GeV) = A_N (100 GeV)
i.e. no energy dependence
[$0.009 < |t| < 0.022$ $(\mathrm{GeV}/c)^2$]

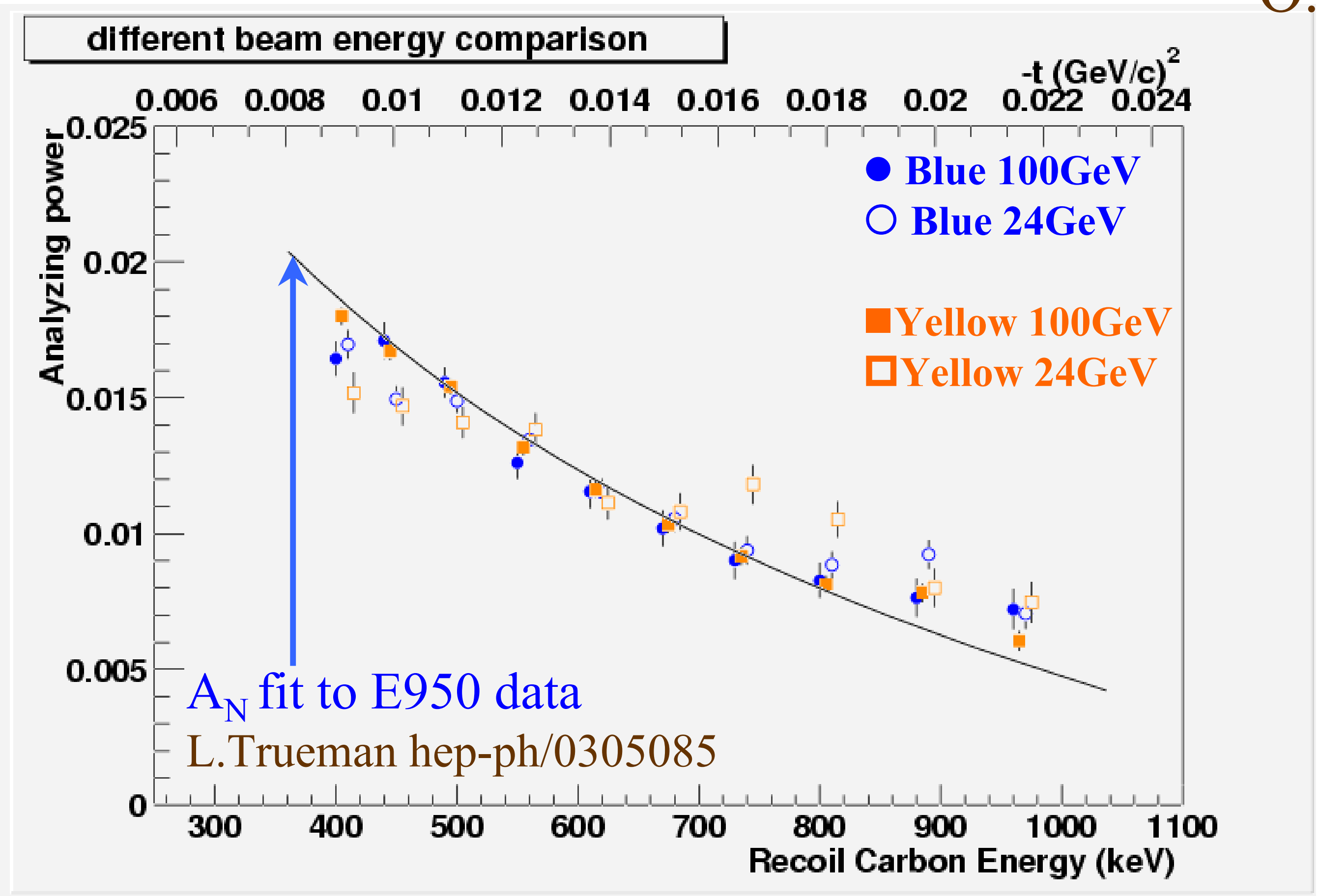
very similar shape of the t dependence
at 24 and 100 GeV

$\Rightarrow$ suggestive of very small
energy dependence for A_N between
24 and 100 GeV

systematic error for RHIC data < 30 %

A_N: $p\uparrow C \rightarrow pC$ from RHIC polarimeters

O. Jinnouchi



assuming same A_N (E950) at 24.3 and 100 GeV

RHIC Polarization from Run '03

$$P_{beam} = \frac{1}{A_N} \cdot \varepsilon_N$$

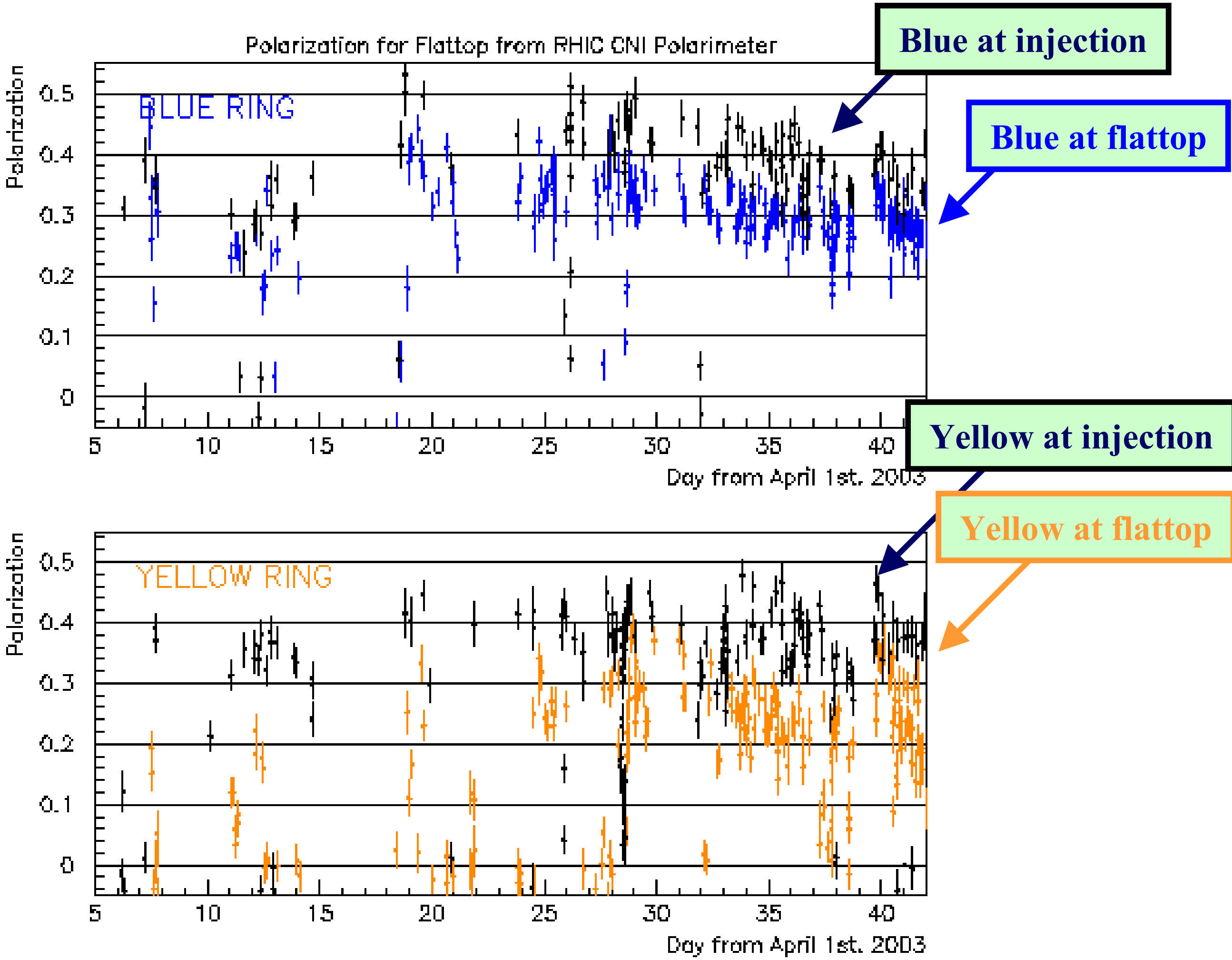
not yet well known
assume same
at injection and flattop

polarization on average

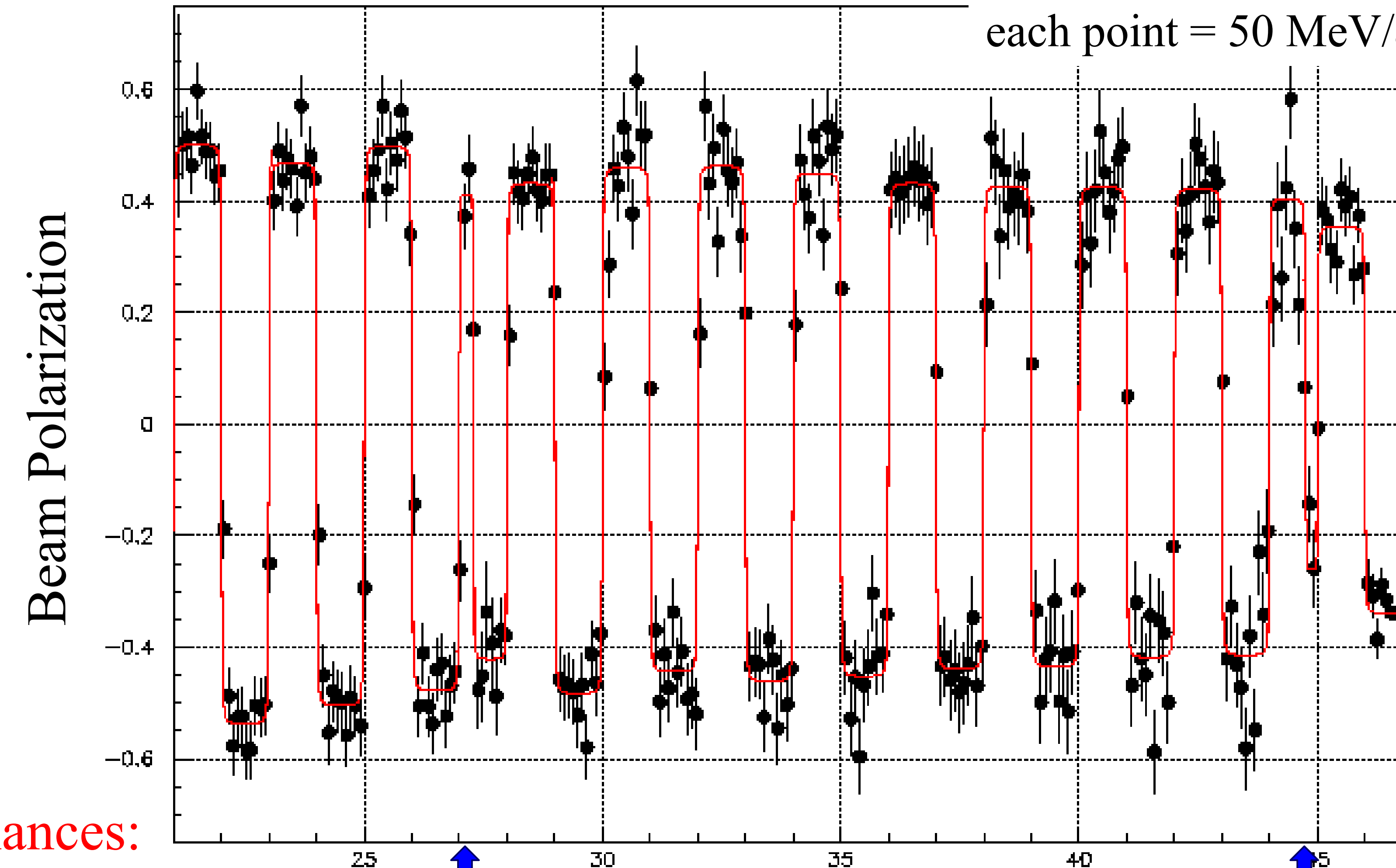
- at injection
  - **Blue ~ 35 - 40%**
  - **Yellow ~ 35 - 40%**

- at flattop
  - **Blue ~ 25 - 35%**
  - **Yellow ~ 20 - 30%**

being analyzed



AGS Polarization during acceleration (ramp)



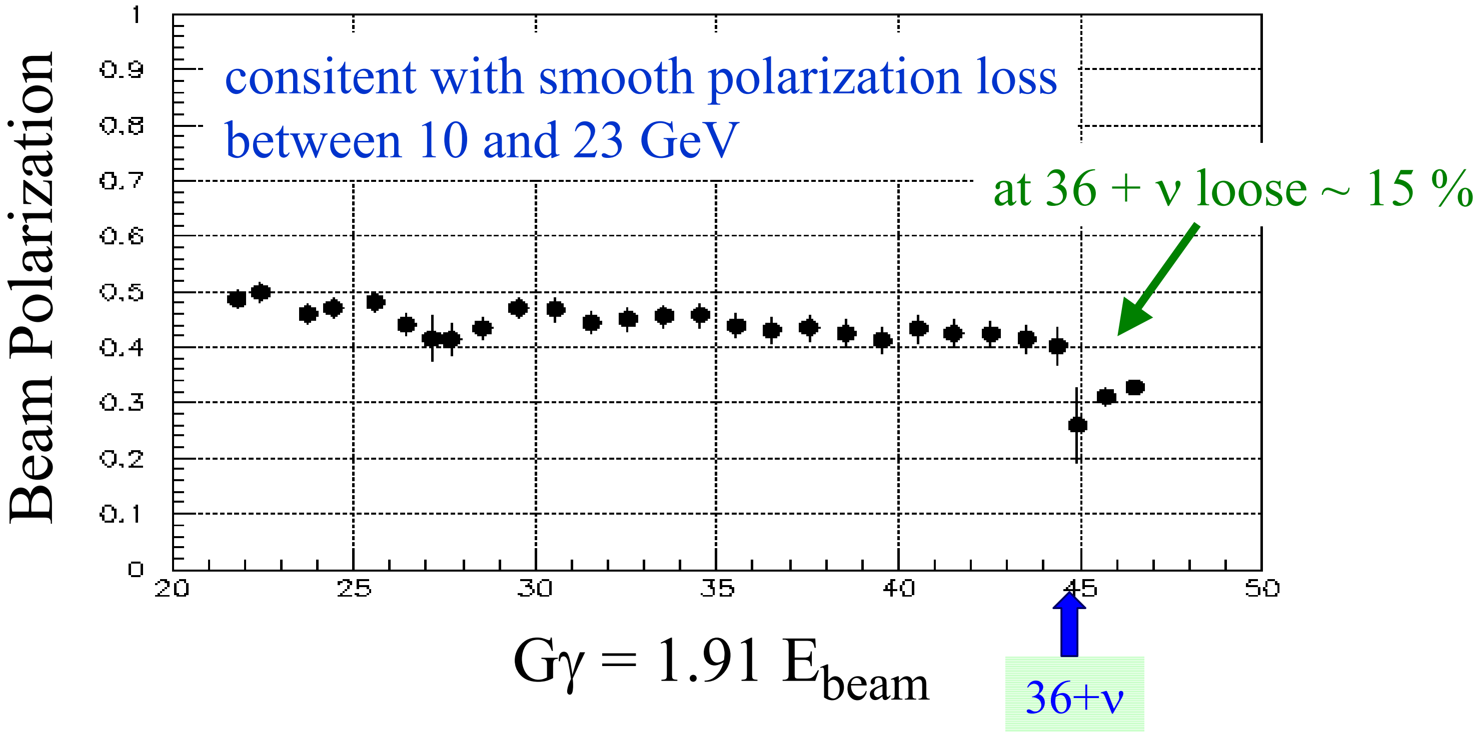
resonances:

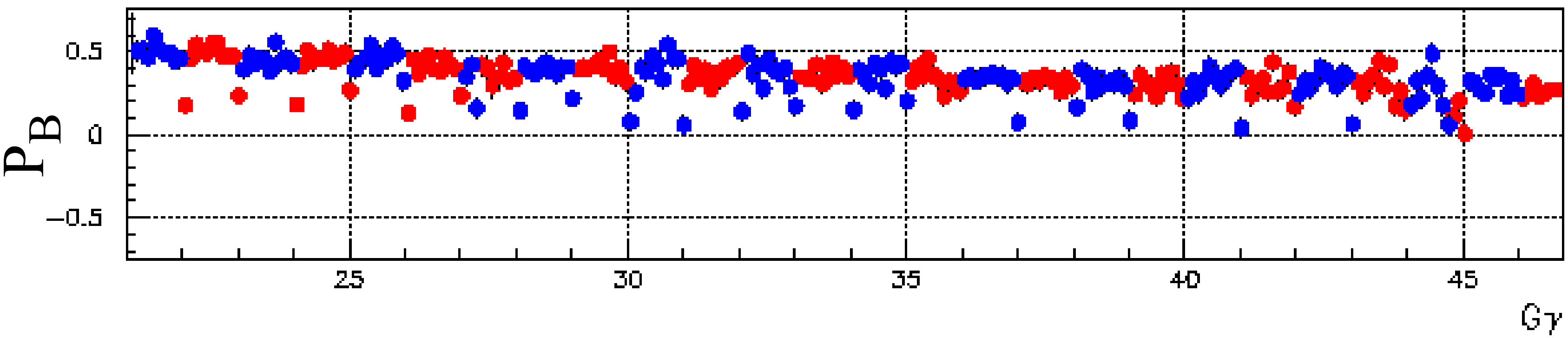
intrinsic: $G\gamma =$ 36-ν 36+ν

imperfection: $G\gamma = n$

$G\gamma = 1.91\ E_{beam}$

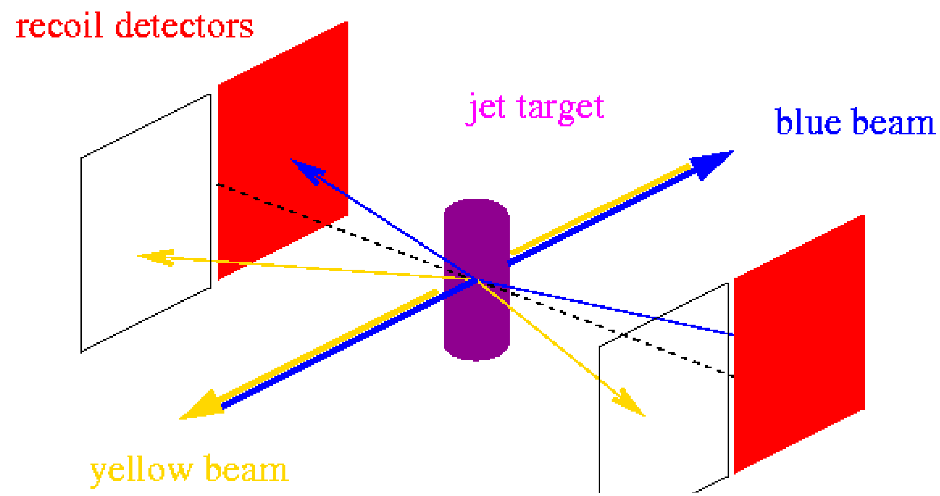
AGS Polarization Systematics



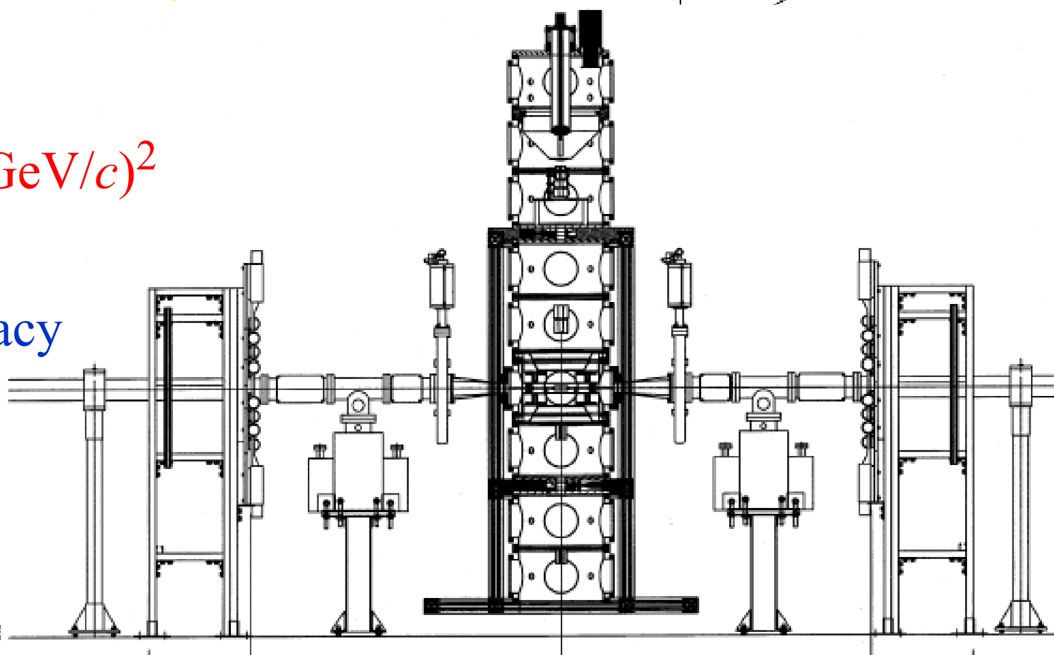


Next: $p^{\uparrow}p$, $pp^{\uparrow}$ and $p^{\uparrow}p^{\uparrow}$ with a Polarized Gas Jet Target

A. Zelenski



- RHIC absolute polarimeter
  calibrate pC polarimeters to < 5%
- Polarized Hydrogen Gas Jet Target
  thickness of > 10^{12} p/cm^2
  polarization > 90%
  almost pointlike
- Silicon recoil detectors
- Rate: 125 Hz for $0.001 < |t| < 0.02\ (\mathrm{GeV}/c)^2$
- Measure A_N^{pp} in *pp* elastic scattering in the CNI region to $\Delta A_N < 10^{-3}$ accuracy
- Install for the ‘04 run
- Initially measure P_B to 10%



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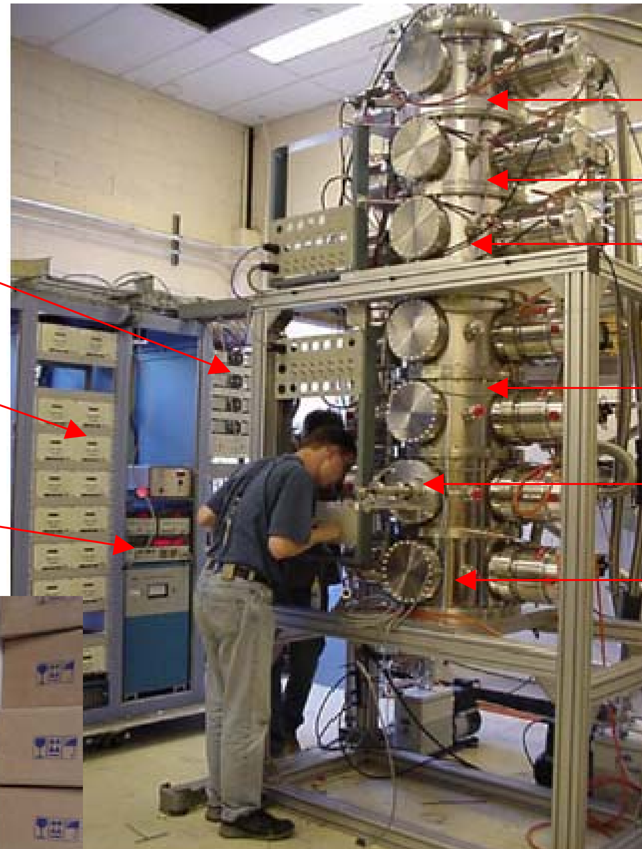
The Polarized Jet Target under construction

Electronics racks

Vac. gauges monitors

Turbo pump controllers

Dissociator RF systems



Dissociator stage

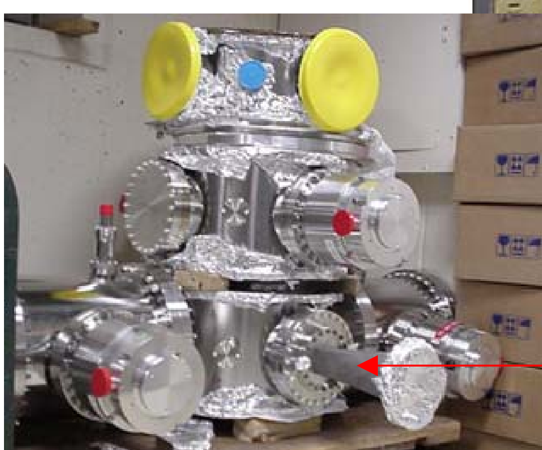
Baffle location

Sextupoles 1-4

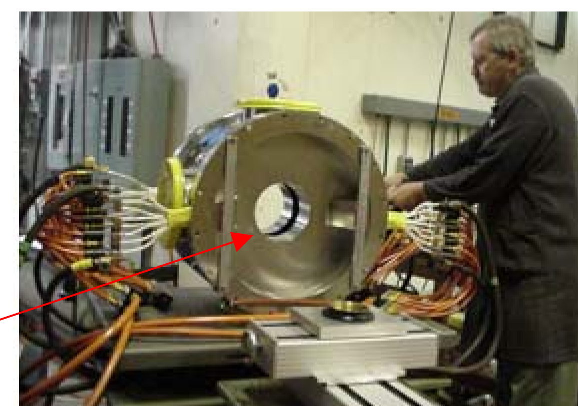
Sextupoles 5-6

Profile measurement

BRP vacuum vessel

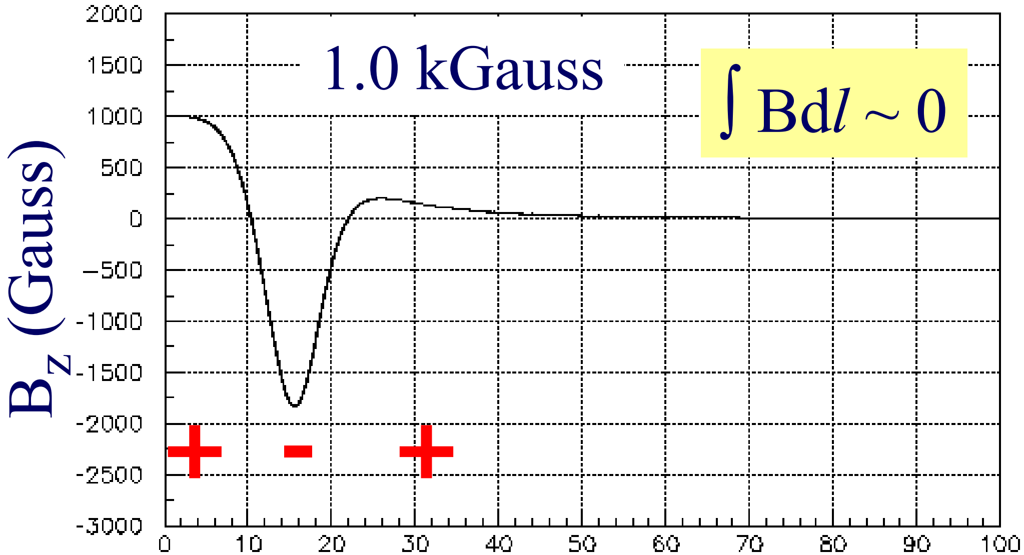


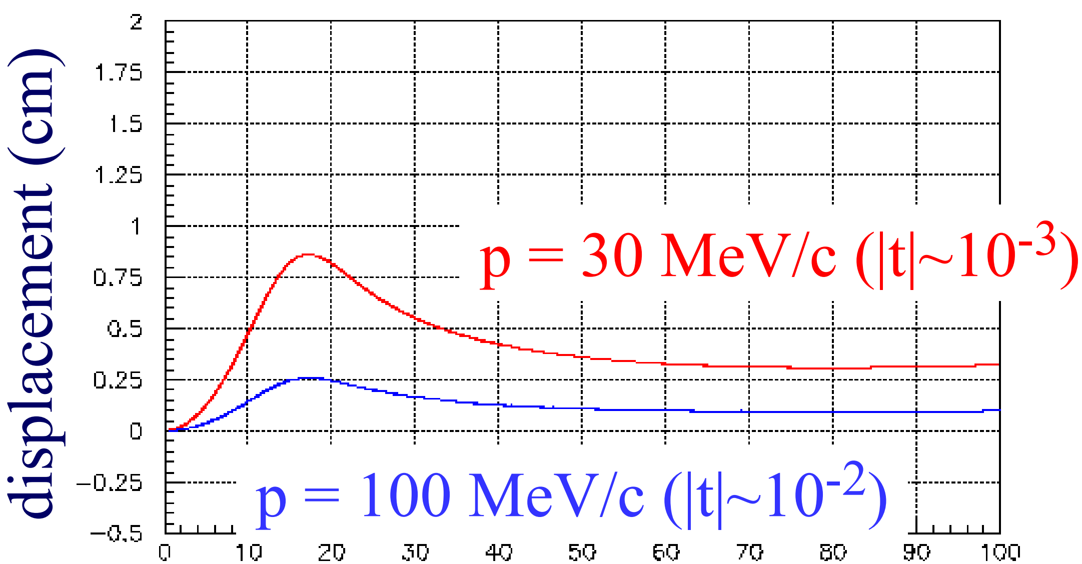
Target chamber &
beam pipe adapters

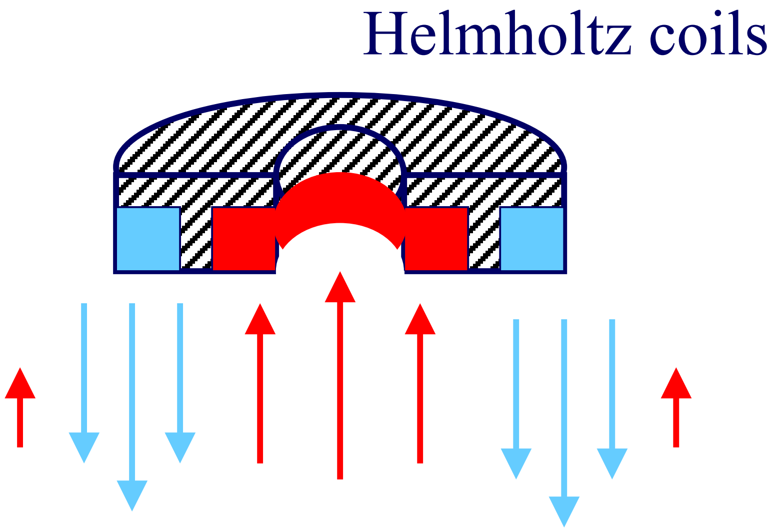


Magnet ready
for measurements

Jet-Target Holding Magnetic Field (1.0)







almost no effect on recoil proton trajectories:

left – right hit profiles & left – right acceptances almost equal (also under reversal of holding field)

Elastic *pp* identification: *t* vs ϑ_R

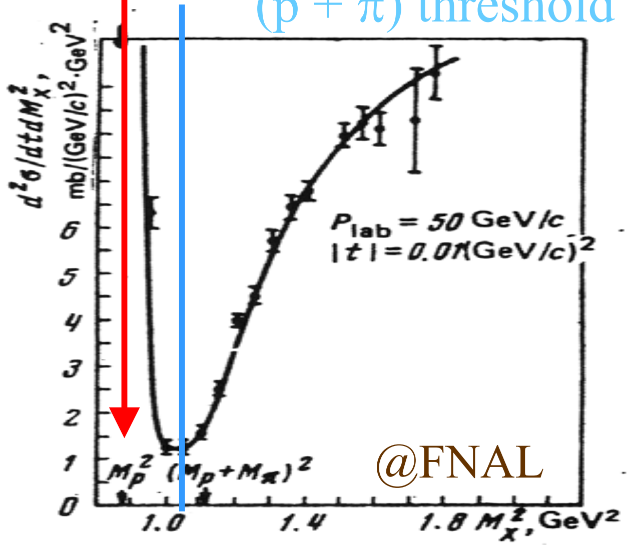
reconstructed from:
1. deposited energy
2. hit position

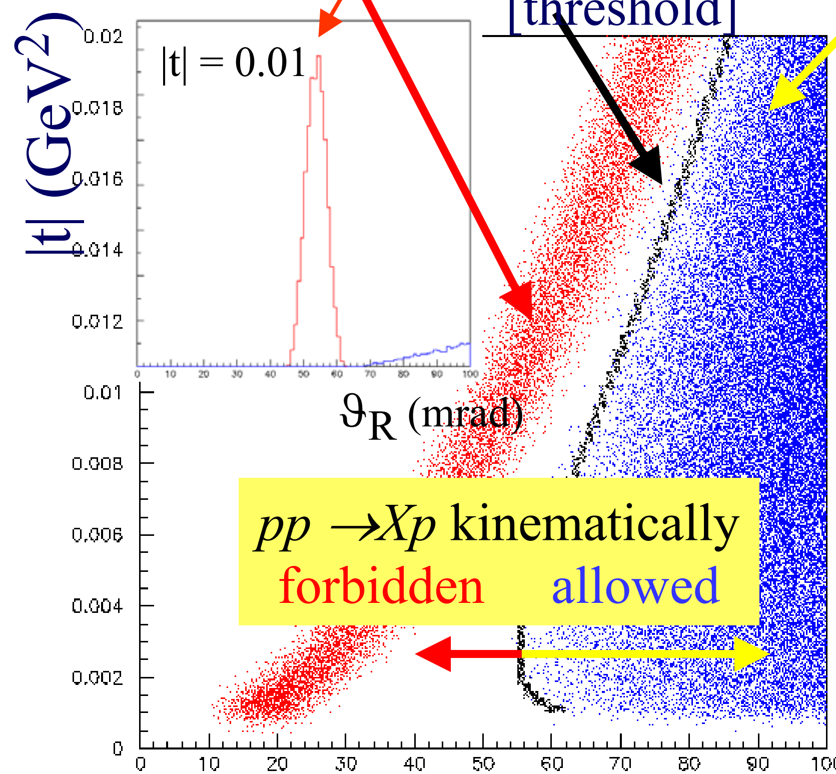
recoil spectrometer resolutions:

$\Delta\vartheta_R$ = targ. ext. / dist. ~ 3 mrad

$|t| = 2\, m_p\, T_{kin}\,;\ \Delta T_{kin} < 50$ keV

$\Delta\tau \sim 2$ ns





$\sigma(pp \to Xp)$ at threshold
$\sim 0.01 \times \sigma$ (*elastic*)!

The Road to P_{beam}

Requires several independent measurements

0 target polarization P_{target} (Breit-Rabi polarimeter)

1 A_N for elastic *pp* in CNI region: $A_N = 1 / P_{target}\, \varepsilon_N'$

2 $P_{beam} = 1 / A_N\, \varepsilon_N''$

1 & 2 can be combined in a single measurement: $P_{beam} / P_{target} = -\, \varepsilon_N' / \varepsilon_N''$

"self calibration" works for elastic scattering only

3 CALIBRATION: A_N^{pC} for *pC* CNI polarimeter in detector kinematical range:

$A_N^{pC} = 1 / P_{beam}\, \varepsilon_N'''$

(1 +) 2 + 3 measured simultaneously with several insertions of carbon target

4 BEAM POLARIZATION: $P_{beam} = 1 / A_N^{pC}\, \varepsilon_N''''$ to experiments

at each step pick-up some measurement errors:

$$\frac{\Delta P_{beam}}{P_{beam}} = \left(\frac{\Delta P_{target}}{P_{target}}\right) \underset{\text{transfer}}{\oplus} \left(\frac{\Delta\varepsilon}{\varepsilon}\right)_{pp} \underset{\text{calibration}}{\oplus} \left(\frac{\Delta A_N}{A_N}\right)_{pC} \underset{\text{measurement}}{\oplus} \left(\frac{\Delta\varepsilon}{\varepsilon}\right)_{pC} \leq 6\%$$

expected precision

transfer calibration measurement

Summary

- measured A_N^{pC} for elastic $pC \to pC$ scattering
  - $0.005 < |t| < 0.05\ (\mathrm{GeV}/c)^2$ & $3.5 < p_{beam} < 24\ \mathrm{GeV}/c$
- $p_{beam} < 10\ \mathrm{GeV}/c$
  - almost no t dependence
  - departure from "CNI" behavior
- $p_{beam} > 20\ \mathrm{GeV}/c$
  - very similar t dependence at 24 and 100 GeV
  - suggestive of small (or no) energy dependence ?
  - consistent with hadronic spin-flip @ 10% – 15% level
- 2004 run
  - extend t range (lower and higher $|t|$)
  - more energy points
  - first measurements of A_N^{pp} for $pp \to pp$ with polarized gas jet target
- phenomenological analysis soon

- polarimetry
  - works reliably, fast measurements of P_{beam} in few min / 30 sec.
  - "absolute" calibration at higher energies $\Rightarrow$ polarized gas jet target